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Lockman and Associates, Monterey Park, CA

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The report is organized into seven sections. Following the introduction and conclusions and recommendations, are sections describing: the three-component gas generation phenomenon; analysis and comparison of alternative gas utilizations including the processes necessary to prepare the gas for use; an evaluation of various landfill design approaches and operations techniques that show promise for enhancing gas generation, recovery efficiency and quality; recommendations for research, development and demonstration projects deemed necessary to develop an adequate data base to proceed with more in depth engineering evaluations of the various options.

Overall, it is shown that landfill gas recovery, processing and utilization is technically feasible and can be economically viable.

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of the environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report presents the results of a study of landfill gas generation, recovery and utilization alternatives based primarily on available information and the current state-of-the-art knowledge. The purpose of the study was to assemble, integrate, analyze and assess the technical and economic feasibility of recovering landfill gas generated by anaerobic bacteria in a landfill environment and processing the gas for various uses as a supplementary or substitute fuel. Emphasis was placed on eliminating inconsistencies and contradictions in the current literature and comparing the economics of alternative gas processing systems to ascertain the best alternatives.

Francis T. Mayo, Director
Municipal Environmental
Research Laboratory

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This report presents the results of a study of landfill gas generation, recovery and utilization alternatives based primarily on available information and the current state-of-the-art knowledge. The purpose of the study was to assemble, integrate, analyze and assess the technical and economic feasibility of recovering landfill gas generated by anaerobic bacteria in a landfill environment and processing the gas for various uses as a supplementary or substitute fuel. Emphasis was placed on eliminating inconsistencies and contradictions in the current literature and comparing the economics of alternative gas processing systems to ascertain the best alternatives.

The report is organized into seven sections. Following the introduction and conclusions and recommendations, are sections describing: the three-component gas generation phenomenon; analysis and comparison of alternative gas utilizations including the processes necessary to prepare the gas for use; an evaluation of various landfill design approaches and operations techniques that show promise for enhancing gas generation, recovery efficiency and quality; recommendations for research, development and demonstration projects deemed necessary to develop an adequate data base to proceed with more in depth engineering evaluations of the various options.

Overall, it is shown that landfill gas recovery, processing and utilization is technically feasible and can be economically viable.

This report was submitted in partial fulfillment of Contract No. 68-03-2536 by Lockman & Associates under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from March 1977 to July 1978, and work was completed as of October 1978.

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LIST OF ABBREVIATIONS AND SYMBOLS

ac -- acre
Al -- Aluminum
BTU -- British thermal unit
°C -- degrees Centigrade
CH_4 -- methane
$C_6H_{12}O_6$ -- glucose
$C_{18}H_{36}O_2$ -- stearic acid
CH_3CH_2OH -- ethanol
CH_3COOH -- acetic acid
cm -- centimeters
CO_2 -- carbon dioxide
cu -- cubic
d -- day
DLFG -- dehydrated landfill gas
Eh -- oxidation-reduction potentials
EPA -- U.S. Environmental Protection Agency
ERDA -- U.S. Energy Research and Development Agency, now Dept. of Energy
°F -- degrees Fahrenheit
Fe -- iron
ft -- foot
gal -- U.S. gallon
ha -- hectare
H_2 -- hydrogen
H_2O -- water
in -- inch
kW -- kilowatt
kWh -- kilowatt-hour
kg -- kilograms
kJ -- kilojoules, a measurement of power
kN/sq m -- kilo Newtons/square meter, a measurement of pressure
l -- liter
lb -- pound
LFG -- landfill gas
M -- thousand
MM -- million
m -- meters
mi -- miles
min -- minute
N_2 -- nitrogen

LIST OF ABBREVIATIONS AND SYMBOLS - continued

O_2 -- oxygen
pH -- negative logarithm of the hydronium ion concentration; the range extends from 0 to 14 with 7 being neutral.
psig -- pounds per square inch gauge
R&D -- research and development
scf -- standard cubic foot
scfm -- standard cubic feet per minute
sec -- second
sq yd -- square yard
Schedule 80 PVC -- plastic (polyvinylchloride) pipe with certain specifications
3ϕ -- three phased electrical power
ULFG -- upgraded landfill gas

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This report represents the cumulative experience and technical knowledge of many individuals on an emerging state-of-the-art technology. Many of the contributors listed have also been instrumental in the research, development and/or implementation of the processes and technologies discussed; or have developed many of the empirical values on gas generation and well construction reported herein. Their many contributions to this scientific field as well as to this report are warmly appreciated. Thanks go to Robert K. Ham, Ph.D., P.E.; Kenneth K. Hekimian, Ph.D., P.E.; Stanley L. Katten, P.E.; Wilbur J. Lockman, P.E.; Ronald J. Lofy, Ph.D., P.E.; Donald E. McFaddin, P.E.; Edward J. Daley, P.E.; and the staff of Reserve Synthetic Fuels, Inc., of Signal Hill, California.

SECTION 1

INTRODUCTION

Interest in the generation, recovery, processing and use of landfill gas for various applications has been slowly gaining momentum during the last half decade. Landfills are the most prevalent method for disposal of solid wastes in the United States. Similarity of landfill gas to sewage sludge digester gas, which has been used as a supplementary fuel in sewage treatment plants for a number of years, and the growing need to effectively control odor and migration of landfill gas have given considerable impetus to the development of landfill gas recovery, processing and utilization. An important difference is that while essentially the same degradation process takes place in a sewage sludge digestor that occurs in a landfill, moisture content, temperature, homogeneity of waste materials and presence of undesirable gases such as oxygen and nitrogen are much more difficult to control in a landfill

Under EPA sponsorship, research and development work has focused on the refinement of sanitary landfill design and operational techniques, and particularly on pollution avoidance such as leachate control and the minimization of leachate formation. EPA documents have been published on landfill design, operation and pollution control. However, until recently, little attention had been paid specifically to the potential recovery and utilization of the gas produced by the decomposition of organic material in the landfill environment. The emphasis has been on minimizing gas production, and when necessary, controlling its movement in order to avoid creating explosion and fire hazards on adjacent properties and on the landfill itself. Thus the deliberate production of landfill gas expressly for use as a supplementary fuel or to generate intermediate energy products constitutes a distinct change in direction from that formerly followed.

Although there have been at least three EPA publications on landfill gas projects,[1.2,3] each has covered a site specific case or a particular phase of a gas development project rather than treated the broad subject in an inclusive but general manner. The recent emphasis of other EPA documents, handbooks and reports on various aspects of sanitary landfilling, has been on managing and controlling leachate production, and gas production and migration.[4,5,6] However, the focus of these publications has not been to provide information on the technology; techniques for enhancement; methods for recovery, processing, delivery and utilization of landfill gas; the costs of recovery and processing; and the economics of the total system for alternative utilizations. The question of how recovery of energy from solid waste in the form of landfill gas compares with other methods for waste-to-energy recovery or conversion has remained largely unanswered to this time.

The objectives and scope of this study together with the general approach and methodology used are beiefly summarized below.

OBJECTIVES AND SCOPE

The overall objective of this study was to explore the technological and economic feasibility of recovery and utilization of landfill gas. Sub-objectives included were:

1. Review and analyze available knowledge of the landfill gas generation process; and define gas composition, production rate, total quantity, production duration and those specific characteristics that influence the above parameters.

2. Examine and analyze alternative utilizations of landfill gas at the various quality levels that applicable processes can feasibly produce and define minimal quantities necessary to achieve economic viability.

3. Summarize landfill design and operating procedures and evaluate alternative design and operational techniques that show promise of enhancing landfill gas generation including relationships and affects on leachate control.

4. Based on existing knowledge of landfill gas generation mechanisms and data uncertainties with regard to alternative utilizations and comparative standing of landfill gas recovery with other waste-to-energy processes, prepare recommendations for further research and development projects and demonstration programs necessary to make the most attractive alternatives available for implementation.

APPROACH AND METHODOLOGY

The general approach used was to review, evaluate, analyze and refine available information and knowledge with emphasis on that developed most recently. Assembly and analysis of unpublished information, and interviews with individuals involved in on-going demonstration and commercial landfill gas development projects were included. To the extent possible, contradictions and conflicts in available information were resolved through the application of additional analysis and the most recent experimental data.

The major constraint on the study was that no new research or development work was to be performed, although unpublished information could be added as appropriate. However, some new concepts and improvements to existing approaches were developed as a result of the various technical and economic feasibility analyses conducted, and from comments and suggestions of several experets in the field of landfill gas generation and recovery, gas processing and utilization.

The research and development, and demonstration project recommendations were developed through a careful assessment of the information generated in each of the study tasks. Emphasis was placed on identifying that data and information normally required by decision makers, that is lacking or exists at inadequate confidence levels.

SECTION 2

CONCLUSIONS

Methane generation is strongly influenced by the availability of balanced supplies of decomposible solid waste plus satisfaction of compatible environmental requirements that promote the growth of methanogenic bacteria.

It is difficult to accurately replicate a portion of a landfill in the laboratory or at a field test site such that important conditions that promote or constrain bacterial activity and gas generation can be accurately measured over long periods of time. It has not been possible to determine methane generation characteristics up to this time experimentally with a high level of certainty.

Theoretical methane generation from typical municipal solid waste (residential, commercial and light industrial), assuming complete transformation of all available organic carbon, ranges from 0.43 to 0.51 std cu m/kg (6.9 to 8.1 std cu ft/lb) of as-received (wet) waste, with 0.45 std cu m/kg (7.2 std cu ft/lb) being representative. Theoretical gas composition would be 54 percent methane and 45 percent carbon dioxide with a higher heating value of 19966 kJ/std cu m (535 BTU/std cu ft).

Estimates of actual production are in the range of 0.16 to 0.25 std cu m/kg (2.5 to 4 std cu ft/lb) of wet waste based on empirical findings that approximately half of the available organic material is actually decomposed during the period that collection is likely to be economical, generally taken as the half-life of the decomposition process.

When the practical aspects of recovery of landfill gas are taken into account (recovery efficiency, boundary losses, collection losses and gas generation before and after recovery is in operation, etc.), current estimates of gas recovery range from 0.013 to 0.047 std cu m/kg (0.2 to 0.75 std cu ft/lb).

Rate of gas production contains similar uncertainties with currently accepted values ranging from 0.006 to 0.038 std cu m/kg (0.1 to 0.6 std cu ft/lb) of wet waste per year with a commonly used rule of thumb being about 0.01 std cu m/kg (0.16 std cu ft/lb) per year. Composition of landfill gas, based on samples analyzed, ranges from 45 to 65 percent methane with the most common values lying between 45 and 55 percent; the balance being primarily carbon dioxide, with smaller amounts of hydrogen, oxygen, nitrogen and traces of other gases.

The gas generation period of a landfill depends upon waste composition (in terms of readily, moderate and difficult to decompose components), internal moisture content, temperature and other environmental factors. In general, a mature landfill that has reached its maximum gas generation rate, variously estimated to occur between one and five years after completion, will produce gas at a high rate for at least six to ten years and will continue to produce gas at lesser rates for between thirty and 100 years.

Optimum moisture content of landfilled waste for maximum gas generation is reported to occur at between 30 and 50 percent wet weight, although there are landfills in dry climates with measured moisture content at or below 20 percent wet weight that are generating gas. Optimal temperatures range from 30 to 40°C (86 to 140°F) with temperatures much below 15°C (59°F) appearing to severely limit methogenic bacteria activity.

The minimum size or volume of a landfill for economic gas production is not directly related to the gas generation mechanism. Rather, it is dependent upon the economics of gas recovery wells and collection system, processing equipment, delivery system and final gas use. In general, assuming that a landfill is suitably "mined" when recovery well influence areas encompass all gas generating waste volumes, a minimum size landfill holds no less than about two million tons of municipal solid waste. Such a landfill near peak generation rates is estimated to be capable of producing between 28.32 and 33.98 cu m/min (1000 and 1200 cu ft/min) of raw gas, which is equivalent to about 759 MM kJ/day (720 MM BTUs/day).

Minimum landfill site fill area size for landfill gas systems to have strong economic viability range from about 11.3 ha (28 ac) for a fill with an average depth of 45.7 m (150 ft) to about 31.6 ha (78 ac) for one with an average depth of 15.2 m (50 ft). Fills of these sizes are expected to generate about 50976 std cu m/day (1.8 MM std cu ft/day) of landfill gas with a unit cost of about $1/1.054 MM kJ ($1/MM BTUs) of dehydrated product. Sites of about one-half the desirable minimal size can be viable provided unit costs about 50 percent higher are acceptable.

Raw landfill gas must be consumed on site because moisture and other corrosive constituents prevent pipeline transport.

Insufficient reliable quantitative data is available on landfill gas generation rates, total gas production, recovery efficiency and variations in gas composition over the long term.

Information on landfill design approaches and operating techniques to enhance LFG generation and recovery are insufficient to permit assessment in quantitative terms and reasonable evaluation of cost effectiveness.

The optimal geometry of landfills for maximum coverage of recovery well influence areas without unnecessary overlaps or missed areas, is an approximately square or rectangular fill area with side dimensions of multiples of about 68.6 to 76.2 m (225 to 250 ft).

Use of landfill gas in dehydrated form as a supplement to or substitute for natural gas shows the greatest promise from standpoints of technical and economic feasibility and particularly because of applicability to landfills of the broadest variation in size and gas flows. This process utilization is suitable to operations by either private enterprise or local government entities.

Further upgrading of landfill gas by removing carbon dioxide, removing both carbon dioxide and nitrogen, or removing only carbon dioxide and sweetening with about one percent propane are shown to be processes too expensive to be economically viable for operation by private enterprise and can be operated by local government on a break-even basis only for landfills of larger sizes when sold at wholesale rates to local utilities.

Generation of steam or electricity using raw landfill gas as the fuel and sold to users at retail prices is technically and economically feasible for both private enterprise and local government operations at modest landfill gas recovery rates.

Any of the three prime movers using raw landfill gas as the fuel to generate electricity can be economically feasible for local government operations when sold to local utilities at wholesale prices. Conversely, only electricity generated by gas turbine-generator sets sold at wholesale to local utilities is economically feasible for private enterprise.

The minimum landfill gas flows needed for economic viability for both private enterprise and local government implementation of the nine landfill gas uses studied are presented in Table 1.

An assessment of various design and operation alternatives for the enhancement of landfill gas generation is presented in Table 2 along with approximate unit cost factors.

TABLE 1. MINIMUM LFG RECOVERY RATE REQUIRED FOR ECONOMIC VIABILITY[a]

LFG process/product	HHV kJ/std cu m	Private enterprise Retail std cu m/min	Private enterprise Wholesale std cu m/min	Local government Retail std cu m/min	Local government Wholesale std cu m/min
I - Dehydration and compression	17727	33.4	N.A.	17.7	N.A
II - Upgrading (H_2O and CO_2 removal)	27990	N.A.	N.F.[c]	N.A.	47.2[b]
III - Upgrading (H_2O, CO_2 and N_2 removal)	36387	N.A.	N.F.	N.A.	141.5[b]
IV - Upgrading and blending (H_2O and CO_2 removal with propane blending)	37320	N.A.	N.F.	N.A.	78.6[b]
V - Steam generation (using raw LFG)	17727	19.7	N.A.	9.8	N.A.
VI - Electricity generation (steam turbine)	17727	35.4	N.F.	11.8	31.4
VII - Electricity generation (gas turbine)	17727	19.7	45.2	9.8	15.7
VIII - Electricity generation (gas engine)	17727	45.2	N.F.	3.9	39.3
IX - Methanol synthesis	17727	N.F.	N.A.	167.0[b]	N.A.

a Based on retail price of \$2.00/1.05 MM kJ (1 MM BTUs) for gas product, \$2.56 for steam, \$0.05/3600 kJ (kWh) for electricity and \$0.092/L (\$0.35/gal) for methanol; wholesale price of \$1.65/1.05 MM kJ (1 MM BTUs) of product for gas, \$0.092/L (\$0.03/kWh) for electricity; ten percent net ROI for private enterprise and local government operations (30 percent gross ROI for private enterprise).

b Break-even operation for local government.

c Can be feasible in unique situations such as Mountain View, California landfill.

N.A. Not applicable.

N.F. Not economically feasible.

TABLE 2 DESIGN AND OPERATIONS ALTERNATIVES FOR LANDFILL GAS GENERATION ENHANCEMENT

Alternative	Potential effectiveness	Cost range ($/sq m)[a]
Site Lining		
Impervious soils	Effective if permeability low	0.25 to 0.42
Treated soils	Effective if permeability low	1.50 to 1.92
Film barrier	Effective with proper base preparation and cover protection	1.05 to 4.60
Asphalt cement with sealant	Effective if properly installed on firm base	3.00 to 4.05
Moisture Control		
Water distribution below cover	Highly effective	0.21 to 0.42
Semi-permeable soil with humectant	Effective if kept moist	0.03 to 0.04 (add 1.00/yr/sq m operating cost)
Controlled uniform negative pressure below cover	Effective if carefully balanced by wells with half normal spacing	0.63 to 0.84 (additional cost for recovery subsystem)
Leachate Collection and Recycling	Effective; pH control may be required	0.13 to 0.29 plus cost of neutralizing chemicals
Operations		
Single water application (truck or hose/spray nozzle)	Effective initially; long term affects unknown	0.02 to 0.03
Waste shredding without daily cover (final cover only)	Affects unknown; may hasten initial LFG generation and should increase waste permeability	4.18 to 8.63 per ton received
Permeable daily cover	Increase ease of movement of LFG within confines of landfill	No additional cost if suitable soil available
Sewage sludge seeding of waste	Affects unknown; may shorten LFG generation initiation time	0.25 to 0.42 (drop charge may exceed spreading costs)
Leachate recycling with pH control	Effective	0.13 to 0.29 plus cost of neutralizing chemicals

[a] Costs estimated for 40 ha (100 ac) fill area landfill.

SECTION 3

RECOMMENDATIONS

Recommended areas for further research and development are:

1. Develop improved baseline data on landfill gas generation and recovery.

2. Test and evaluate techniques such as leachate recycling and preprocessing of waste to enhance landfill gas generation.

3. Optimize landfill design to enhance gas recovery at existing and new landfills.

4. Optimize gas recovery well and collection system design.

5. Improve energy recovery efficiency of landfill gas generation/recovery.

6. Refine cost and economic analysis of landfill gas recovery/ processing/utilization.

7. Develop a handbook or manual on landfill gas recovery/processing/ utilization.

8. Evaluate institutional constraints of landfill gas utilization.

9. Evaluate combustion equipment changes to permit utilization of landfill gas.

Recommended demonstration projects are:

1. Design, construction, and evaluation of improved landfill gas recovery and processing systems.

2. Demonstrate improved steam and electricity conversion processes using landfill gas.

3. Evaluate environmental effects of landfill gas recovery/processing/utilization systems.

SECTION 4

REVIEW OF LANDFILL GAS GENERATION AND CHARACTERISTICS

The processes by which organic components of solid waste are decomposed in sanitary landfills are described. Also discussed are the characteristics of the gas produced, typical composition and the theoretical and estimated realizable quantities produced per unit quantity of solid waste.

The material presented constitutes the results of detailed study and analysis of the available literature, with emphasis on the most recent research findings. The intent has been to clarify to the extent possible, existing explanations of gas generation mechanisms and the resultant gas characteristics.

COMBINED DECOMPOSITION PROCESSES

Organic components of landfilled solid waste decompose by a combination of biological, chemical, and physical processes. Methane gas is produced only through biological decomposition and thus biological processes are of primary importance to this study. However, interdependencies among the three processes require that chemical and physical decomposition also be considered. Biological decomposition is the conversion of carbonaceous components into cellular and partially decomposed matter, and gaseous end products. Chemical decomposition is the hydrolysis, dissolution-precipitation, sorption-desorption or ion exchange of refuse components which results in changed characteristics and greater mobility of the altered refuse constituents. Physical decomposition is the breakdown or movement of waste components by the rinsing or flushing action of water movement, diffusion due to concentration gradients, or flow as a result of pressure gradients.

Physical decomposition is the mechanism by which products of biological and chemical decomposition are transported through and out of the landfill. If there is a high rate of water flow, increased amounts of matter will be dislodged, contaminating the water and making the refuse mass more uniform chemically. Flushing of the biological and chemical decomposition products from the landfill may result in rapid stabilization of the fill material.

The most noticeable indicator of chemical decomposition is the effect of pH on dissolution of matter, especially inorganics. Acidic pH levels will solublize most organics such as metals, hydroxides, carbonates, etc., resulting in increased ion concentrations in the water.

Although physical and chemical decomposition play important roles in a decomposing landfill, biological decomposition appears to be the most important since, for example, it controls the pH levels in a landfill which, in turn, dictate the degree of chemical dissolution. Similarly, except for waste components dislodged by water movement, it is primarily biological decomposition that renders matter available for movement.

Biological decomposition is complex, consisting of a multitude of biologically mediated parallel and sequential pathways by which matter is decomposed completely or, depending on conditions, partially decomposed to various end products. Environmental variables, such as temperature, availability of oxygen, and moisture, combine with the chemical make-up of the matter and the previous history of the landfill to determine which biological decomposition mechanisms are active at a given time and location within a landfill. Landfill history relates to age, original composition, prior decomposition, availability of nutrients, presence of necessary micro-organisms, etc.

BIOLOGICAL DECOMPOSITION

Biological decomposition takes place in three stages, each of which has its own environmental and substrate requirements, and its own characteristic products and effects. When solid waste is first placed in a landfill, some oxygen is invariably entrapped as well. Aerobic micro-organisms, while the oxygen lasts, degrade organic matter into carbon dioxide (CO_2), water, partially degraded residual organics and heat. Aerobic decomposition is characteristically rapid relative to subsequent anaerobic stages of decomposition because the most readily degradable matter in the waste is available to these micro-organisms producing temperature increases as high as 35 to 40° C and large amounts of carbon dioxide. The carbon dioxide content during this initial stage may go as high as 90 percent with a corresponding decrease in oxygen. Part of the carbon dioxide dissolves in any water present resulting in acidic pH levels, the balance remains in the gaseous phase. Theoretically the nitrogen content does not change since a mole of carbon dioxide is produced for each mole of oxygen consumed.

As the oxygen is depleted, a second group of micro-organisms, the acid formers, becomes dominant. These organisms are facultative; i.e., they can tolerate oxygen but are not dependent on it being present. Characteristics of this second stage of decomposition are rapid evolution of carbon dioxide, little production of heat, and production of partially degraded organics, of which organic acids are a special concern. The production of both carbon dioxide which dissolves readily in water and organic acids results in a lower pH than in the aerobic stage. The acidic conditions tend to dissolve inorganics in the waste. Partially degraded organics, acidic pH and associated high inorganic concentrations result in contamination of available moisture during this stage.

After all the oxygen has been consumed, and strongly reducing conditions established, the methane (CH_4) forming micro-organisms become dominant. The methane formers are strictly anaerobic, oxygen being toxic to them. These organisms work relatively slowly, but efficiently, forming carbon dioxide, water and methane, with little production of heat. If the rate of water movement through the refuse is low enough, these organisms efficiently decompose organic matter into gaseous end products, reducing the amount of partially degraded organic matter in the water. Because of the relatively slow rate of decomposition (characteristic of these organisms) and the increasingly refractory nature of the waste, the carbon dioxide content of the gas typically decreases and the moisture pH rises, thereby reducing the amount of dissolved inorganic matter. This stage is called the methanogenic stage.

Landfills normally undergo at least two, if not all three, of the three stages of biological decomposition simultaneously. The methane forming micro-organisms, for example, require a symbiotic relationship with acid-formers, some of which are facultative, which virtually assures that at least some of the organisms present during the facultative stage are also present in the methanogenic stage. One view holds that the transition from facultative to methanogenic stages involves the addition of methane formers when conditions conducive to their growth appear. It is also evident that portions of a landfill near the surface are more likely to be exposed to oxygen due to diffusion and barometric changes. As a result, some parts of the fill may be characterized over the entire site life as undergoing facultative decomposition while other parts remain predominantly anaerobic. It is also true that the refuse is so heterogeneous that differences in decomposition processes are likely to occur in adjacent segments. For example, concentrated amounts of food wastes will deplete oxygen rapidly, whereas demolition wastes combine with oxygen much more slowly.

The result of these complications is that a landfill may be characterized as undergoing predominantly one type or stage of decomposition at a given time although other concurrent processes are possible at some lower level of activity. Measurements at a landfill may indicate a predominant type of decomposition, but it is the dynamic growth and contraction of the relative level of activity of the chemical, physical, and the three biological decomposition mechanisms that determine the interactions within a fill.

METHANOGENIC DECOMPOSITION

Methanogenic decomposition is of primary importance to this study and warrants further discussion. Recent information suggests that there are really three types of bacteria working together to form methane: The fermentors, acetogenic and methane formers. The fermentors reduce cellulose, lipids and proteins to organic acids, of which acetic acid is of major importance. Other products are alcohol, hydrogen, carbon dioxide, ammonia, and sulfide. Some of these organisms are strict anaerobes, other are facultative so they are not excluded from being active during either the facultative or methanogenic stage of decomposition. Acid hydrolysis and enzymatic attack are used initially to break down long-chain organics for further decomposition. The acetogenic bacteria are thought to be bacteria which oxidize longer chain organic acids (other than acetic) and other select substances such as alcohols to acetate and hydrogen. They have not been positively identified, but one known reaction is conversion of ethanol to acetic acid as follows:

$$CH_3\ CH_2O\ H + H_2O \longrightarrow CH_3\ COOH + 2H_2$$

There exists continuing controversy over the importance of hydrogen as a precursor of methane formation. One theory is that hydrogen is the major precursor. Another is that acetate is of major importance. It is known that hydrogen is utilized readily by the methane formers, that the bacteria producing hydrogen do so rapidly yet are inhibited by environments containing too much hydrogen. Thus, they are killed by their own concentrated metabolic by-products and are dependent on other bacteria to remove the hydrogen for hydrogen formation to continue. These characteristics fit the observation that hydrogen normally is found in low concentrations in landfills except for a short period prior to methane formation when elevated levels up to 2 to 4 percent may be observed.[8]

All methane formers are able to use hydrogen and carbon dioxide to form methane as indicated:

$$4\ H_2 + CO_2 \longrightarrow CH_4 + 2\ H_2O$$

and many of them are able to use formate, acetate and possibly propionate and butyrate substrates as well. Of these, acetate is found in large amounts during methane production and is assumed to cleave as follows to produce methane:

$$CH_3\ COOH \longrightarrow CH_4 + CO_2$$

The methane formers use ammonia as a nitrogen source and are not known to use the more oxidized forms of nitrogen. They can also use sulfides and other forms of sulfur, excluding sulfate as a source of sulfur. Methane formers are killed by oxygen and in general require strongly reducing conditions represented by oxidation-reduction potentials (Eh) on the order of -200 to -300 MV. Because of the complex inter-relationships between the various micro-organisms, each of which has its own specific nutrient, substrate, and environmental requirements, it is not surprising that a broad mixture of nutrients and bacterial species is conducive to rapid methane formation.[3]

From an energy standpoint, the most favorable methane and carbon dioxide production occurs when C, H, and O occur in the ratio CH_2O (carbohydrate). Glucose, for example,[9] is converted biologically to methane according to the following reaction:

$$C_6\ H_{12}\ O_6 \longrightarrow 3CH_4 + 3\ CO_2 + 70\ \text{kcal}$$

Little energy is lost in the process, for 90 percent of the energy of the glucose remains in the methane, as shown by:

$$3CH_4 + 6O_2 \longrightarrow 3\ CO_2 + 6H_2O + 630\ \text{kcal}$$

Since carbohydrates are the largest class of organics found in typical urban solid waste, a high potential for methane gas generation exists.

The methane formers have rather stringent environmental and substrate requirements and even more strict requirements for rapid methane gas formation. Permissible constituent concentration levels and the various requirements for acceptable sewage sludge digestion have been established, and are being evaluated for landfills.[8] Moisture is necessary and there is some lower limit below which little or no methane formation occurs. The problem of knowing at what levels moisture content or other environmental factors in a landfill are the cause of lack of methane production is difficult. It is clear, however, that methane formers work better as the moisture content increases. It has been observed that maximum gas production occurs at 60 to 80 percent (wet weight) moisture content in test landfills.[10,11] It is probable that conditions may be sub-optimal for rapid methane formation in some landfills in dry climates.

Another requirement for methane formation is pH levels close to neutrality. Optimal pH conditions are reported to be 6.7 to 7.2 for sewage sludge digestion, and 5.5 to 9.0 for organics decomposition in soils.[8] Associated with pH requirements are alkalinity and organic acid requirements. A minimum alkalinity of 2000 mg/l as $CaCO_3$ is considered necessary, presumably to insure sufficient buffering capacity to avoid pH variations and formation of large amounts of undissociated organic acids. A maximum permissible organic acid concentration of 3000 mg/l as acetic acid is reportedly a requirement, with improved methane production occurring at the lower levels.

As mentioned previously, strong reducing conditions are necessary, with oxidation-reduction potential (Eh) requirements of -200 MV in soils and sewage sludge digestion. Some methane formers require Eh values of -300 MV.

Temperature is important, with optimal mesophilic temperatures of 30 to 40° C and optimal thermophilic temperatures of approximately 50 to 55° C.[8] At higher temperatures, methane production drops off quickly. The organisms work progressively slower as this minimum of approximately 10° C is approached. Variations in temperature can also upset methane formation. Most temperature data are reported for test landfills, and not for properly instrumented full-scale landfills under a variety of climatic conditions.[7] Nevertheless, it appears that maximum expected temperatures are in the 35 to 40° C range and are attained as a result of aerobic decomposition soon after landfilling. As a landfill ages, temperatures drop typically to the 20° C range, depending primarily on climate. Lower temperatures are possible and, in fact, portions of one landfill in a northern state were found to be frozen after more than a year after placement under freezing conditions. This attests not only to the wide range of temperatures experienced, but also to the insulating properties of refuse. It is apparent that in some landfills the temperature will be so low as to preclude widespread methane formation and that in most landfills temperatures will be less than optimal. The insulating effect is beneficial, however, in avoiding rapid temperature changes and the attendent inhibitation of methane formation.

GAS PRODUCTION AND COMPOSITION DURING METHANE FORMATION

The generalized equation describing gas generation by the methane formers, in concert with various associated micro-organisms such as the fermentors and acetogenic bacteria is widely reported for a substrate of overall composition $C_aH_bO_cN_dS_e$ as:

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right) H_2O \longrightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right) CH_4$$

$$+ \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right) CO_2 + dNH_3 + e\ H_2S$$

Assuming that the various components of the waste are available simultaneously, the overall solid waste composition may be inserted into this equation to estimate gas composition and total methane formation. Using this approach, Boyle calculated theoretical gas production using data developed by Bell for typical urban refuse composition.[13,14] These data are summarized in Table 3 and indicate the composition of typical waste to be 28 percent carbon, 3.5 percent hydrogen, 22.4 percent oxygen, 0.33 percent nitrogen, and 0.16 percent sulfur. In addition, the waste contained 24.9 percent noncombustibles and had a moisture content of 20.7 percent (wet weight). The result was 0.45 std cu m (7.2 std cu ft) of gas/kg (lb.) wet refuse as received, having a composition of 54 percent methane and 46 percent carbon dioxide.

This estimate oversimplifies the complex process of decomposition. However, if it is understood to be the maximum theoretical yield which will never be achieved in any reasonable period of time, it has value. This equation assumes that all organics will be decomposed. However, lignin and plastics, for example, are not degradable to any practical extent under anaerobic conditions. Further it assumes that all degradation occurs anaerobically so that all organic matter is decomposed to methane and carbon dioxide. Thus, any matter leaving the landfill, whether as a gas or as a component of leachate, would not contain any organic matter except methane which is not the case. Also it assumes that all refuse components are available to the organisms simultaneously so that a balance of substrates and nutrients are available at all times. This is also not likely to be the case. Components such as food wastes with high sugar, fat and starch contents are more readily degradable than components such as paper, garden wastes, wood and natural fiber textiles which contain large amounts of cellulosic materials. Finally, a portion of the degraded matter will be utilized for bacterial cell systhesis, which is not included in the generalized equation. More properly, the value calculated from the equation should be reduced by an amount in the proportion of $C_5H_7O_2N$ which is the average bacterial cell chemical composition. Anaerobic cells are produced typically at the rate of 0.03 to 0.15 grams per gram COD consumed depending on the substrate. While the error is generally small, it may be significant in some

TABLE 3. COMPOSITION AND ANALYSIS OF AN AVERAGE MUNICIPAL REFUSE FROM STUDIES BY PURDUE UNIVERSITY[8]

Component	Percent of All Refuse by Weight	Moisture (Percent by Weight)	Analysis (Percent Dry Weight)						
			Volatile Matter	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Noncombustibles
			Rubbish, 64%						
Paper	42.0	10.2	84.6	43.4	5.8	44.3	0.3	0.20	6.0
Wood	2.4	20.0	84.9	50.5	6.0	42.4	0.2	0.05	1.0
Grass	4.0	65.0	-	43.3	6.0	41.7	2.2	0.05	6.8
Brush	1.5	40.0	-	42.5	5.9	41.2	2.0	0.05	8.3
Greens	1.5	62.0	70.3	40.3	5.6	39.0	2.0	0.05	13.0
Leaves	5.0	50.0	-	40.5	6.0	45.1	0.2	0.05	8.2
Leather	0.3	10.0	76.2	60.0	8.0	11.5	10.0	0.40	10.1
Rubber	0.6	1.2	85.0	77.7	10.4	-	-	2.0	10.0
Plastic	0.7	2.0	-	60.0	7.2	22.6	-	-	10.2
Oils, Paints	0.8	0.0	-	66.9	9.7	5.2	2.0	-	16.3
Linoleum	0.1	2.1	65.8	48.1	5.3	18.7	0.1	0.40	27.4
Rags	0.6	10.0	93.6	55.0	6.6	31.2	4.6	0.13	2.5
Street Sweepings	3.0	20.0	67.4	34.7	4.8	35.2	0.1	0.20	25.0
Dirt	1.0	3.2	21.2	20.6	2.6	4.0	0.5	0.01	72.3
Unclassified	0.5	4.0	-	16.6	2.5	18.4	0.05	0.05	62.5
			Food Wastes, 12%						
Garbage	10.0	72.0	53.3	45.0	6.4	28.8	3.3	0.52	16.0
Fats	2.0	0.0	-	76.7	12.1	11.2	0.0	0.00	0.0
			Noncombustibles, 24%						
Metals	8.0	3.0	0.5	0.8	0.04	0.2	-	-	99.0
Glass & Ceramics	6.0	2.0	0.4	0.6	0.03	0.1	-	-	99.3
Ashes	10.0	10.0	3.0	28.0	0.5	0.8	-	0.5	70.2
			Composite Refuse, as Received						
All Refuse	100	20.7	-	28.0	3.5	22.4	0.33	0.16	24.9

cases.[15]

In addition to these equation inaccuracies in the amount of gas produced, there is the likelihood that the composition of the gas measured at the landfill will not be as calculated because of the much higher solubility of carbon dioxide in water than methane, among other reasons. Solubility considerations alone suggest that the greater the availability of water in a landfill and the greater the moisture content of the refuse, the higher will be the methane concentration in the gas even though the amount of gas generated per gram of refuse remains unchanged.

The overall reactions for the anaerobic decomposition of typical solid waste components to form methane are as follows: For cellulose which is a major component of refuse, conversion begins with hydrolysis or enzymatic breakdown of saccharides, of which glucose is the most common. The glucose then breaks down according to:

$$C_6H_{12}O_6 \longrightarrow 3\ CH_4 + 3\ CO_2$$

by pathways as yet uncertain, involving organic acids and acetate, in particular, and probably hydrogen as intermediates. A fatty material such as stearic acid degrades according to:

$$C_{18}H_{36}O_2 + 8\ H_2O \longrightarrow 13\ CH_4 + 5\ CO_2$$

To the extent specific compounds in the waste can be determined, it is possible to refine the result obtained from the overall refuse composition. Golueke, for example, divided the organic portion of the solid waste into newsprint (33 percent), Kraft paper (40 percent), and other organics (27 percent) to calculate a total gas production of 0.55 cu m/kg (8.8 cu ft/lb) dry volatile matter.[16] Such an approach reduces the errors inherent in use of the overall elemental analysis, and is particularly useful for incorporating rate constants to predict the effect on non-homogeneous decomposition rates from component to component.

Gas Quantity

Reliable data on total gas production from decomposition of waste are difficult to obtain as is borne out by the high variability of available data. Ideally, a landfill must be monitored over its entire decomposition life to determine total gas production. Obviously, the time required to develop such information is an obstacle. An additional problem inherent in measuring gas production is the change in landfill conditions brought about by the gas collection techniques. If one attempts to enclose a landfill for gas measurement, using a wetted clay seal, for example, the decomposition process will be changed, affecting the results directly. Water movement in the landfill will be changed, normal gas flow patterns will be disrupted, etc., possibly invalidating the results. Small volumes of refuse have been decomposed in lysimeters and the gases evolved measured, but the difficulties in simulating not only typical landfill conditions but also the variations in conditions brought about by climatic events makes the applicability of such data to full-scale landfills questionable. Many studies which might have produced gas generation data are useless as far as methane production is concerned because methane production was never achieved. In some cases insufficient time was allowed and in other cases the decomposition process did not advance to stable methane production for some unexplained reason. The fact is that it has been difficult to achieve stable methane production in small enclosed volumes (lysimeter studies).

Table 4 summarizes the best available data on total gas generation from solid waste during methane formation. Additional estimates or measured values exist, but these values are not thought to accurately reflect the latest state-of-knowledge. Necessarily, the higher gas production values are based on theoretical calculations. The nature of decomposition of materials of varied composition and degrees of decomposability suggests that complete decomposition will take a very long time and, in fact, may never be attained completely in practice. One way to circumvent this problem is to relate gas production to the amount of refuse decomposed (e.g., volatile solids or organic carbon lost) and leave it to the user of the data to determine how much decomposition will be of interest for the particular application or landfill of concern.

Table 4 indicates that the theoretical gas production is approximately 0.44 cu m/kg (7 cu ft/lb) of refuse for complete decomposition by methane formers and their associated microbiological co-workers (entries 1, 2, 10, 11, and 12). Variations are due primarily to waste composition differences. Entry 11 is based on measurement of gas collected from a large landfill over a period of one year by a gas withdrawal system installed to limit uncontrolled off-site gas migration. By estimating the tonnage of refuse generating gases which were pumped into the collection system, and knowing the composition and amount of those gases, a value for gas generation per unit refuse weight was calculated over the period of monitoring. Adjustment of constants appropriate to theoretical equations describing the rate of gas generation with time, permited extrapolation of the rates measured over a relatively short time to the total production to be expected over the life of the landfill. Note that the total amount of gas to be produced was based on purely theoretical considerations (generation period and rate of change), and the curves developed were constrained by the calculated total to be produced and on that measured for one year. Therefore, entry 11 total gas production agrees with other purely theoretical approaches.

Consideration of the decomposability of various components of the waste reduces the total gas production to a more feasible maximum of 0.13 to 0.31 std cu m/kg (2 to 5 std cu ft/lb) (entries 3 and 4). The highest measured amounts of gas were produced in digesters in which solid waste was seeded with sewage sludge; mixing provided uniformity of conditions, substrate, and nutrients; and variables such as temperature, time and moisture content were controlled to various degrees to promote methane formation. These results may be practical for controlled decomposition of waste slurries in specially built digesters designed for that purpose, but they are not applicable to landfill conditions except, possibly, as a goal which will probably prove unrealizable even for specially designed and operated land-

TABLE 4. TOTAL LANDFILL GAS (CARBON DIOXIDE AND METHANE) GENERATION FROM MUNICIPAL SOLID WASTE

Sources	Conditions	Basis	Gas production refuse as received* std cu m/kg
1. Anderson & Callinan (17)	Typical municipal refuse	Theoretical	0.41
2. Boyle (13)	Typical municipal refuse	Theoretical	0.45
3. Golueke (16)	Divided organics by component, calculated 0.55 cu m/kg dry volatiles*	Theoretical	0.30
4. Pacey (18)	Weighted organic components by degradability, calculated 0.06 cu m CH_4/kg†	Theoretical	0.12
5. Klein (19)	Digested refuse with sewage sludge, obtained 0.44 cu m/kg volatiles destroyed*	Lab measurement	0.24
6. Hitte (20)	Cites data for digesting refuse and sewage sludge of 0.11 cu m CH_4/kg refuse and sludge, recalculated assuming wet sludge is negligible†	Lab measurement	0.21
7. Pfeffer (21)	Digested refuse at 8 percent solids, 35° C, 30 day solids ret. time	Lab measurement	0.26
8. Schwegler (22)	0.38 cu m/kg refuse destroyed, assumes refuse 50 percent decomposable	Estimated	0.19
9. Hekimian, et al (23)	Observed value for Los Angeles area	Estimated	0.05

(continued)

TABLE 4 (continued)

	Sources	Conditions	Basis	Gas production refuse as received* std cu m/kg
10.	Alpern (24)	530 cu m/t refuse	-	0.53
11.	City of Los Angeles (25)	387 cu m/t refuse, theoretical extrapolation of measured values	Theoretical/measurements in landfill	0.39
12.	Bowerman, et al (3)	0.51 cu m/kg dry refuse, recalculated* based on 0.25 kg org. C/kg	Theoretical	0.40
13.	Blanchet (1)	Calculated from landfill test and theoretical extrapolation over 10 yr	Measurement/ theoretical	0.13
14.	VTN Consolidated, Inc. (26)	"Estimate" for Los Angeles landfills	-	0.05
15.	Merz (27)	Refuse in small lysimeters, wetted with digester supernatant	Measurement	0.013
16.	Merz & Stone (28)	Lysimeter, gas production very low at end of 2-1/2 yr study	Measurement	0.004
17.	Rovers & Farquhar (29)	Lysimeter, gas prod. continuing at low level at end of 200 day study	Measurement	0.003
18.	Streng (30)	Lysimeter, gas. prod. over approximately 2 yr, continuing	Measurement	0.039
19.	Chian (31)	Small lysimeters, cell 4 only one producing CH_4, gas prod. low after 300 days, recalculated*	Measurement	0.0005

* Corrected to refuse composition of Table 3.

+ Corrected to 53 percent CH_4.

fills. Entries 5, 6, and 7 are examples of digester gas production, 0.22 to 0.25 std cu m/kg (3.5 to 4 std cu ft/lb) of refuse being a representative range. Entry 7, in particular, provides information on the effect of temperature and solids contact time (e.g., the average period of contact between waste to be decomposed and the micro-organisms), both of which are cited previously as being important landfill variables affecting gas production.

Entries 8, 9, and 14 reflect the most common approach for estimating total gas production; namely, evaluating available information and estimating what is believed to represent a reasonable value for the case in question. For example, one rule of thumb often cited reasons that 0.83 cu m/kg (6 cu ft/lb) is approximately the maximum theoretical gas production from typical refuse, of which one-half will not be generated because of imprefections in the various decompositional processes, resulting in incomplete decomposition. Of this, another half will be lost because it is not produced during the period of active decomposition when gas recovery would be most likely. Finally, only one-half of the amount will be feasible to recover; the remainder being produced near landfill boundaries or between withdrawal wells, etc., and therefore lost. The result is that only 0.047 std cu m of gas/kg (0.75 std cu ft of gas/lb) of refuse is likely to be recovered. Such rules of thumb, tempered by the sparse but steadily increasing amount of field and pilot scale data, has led to commonly accepted figures, such as used in entries 8, 9, and 14.

Entries 15 through 19 are generation rates measured in enclosed test chambers (lysimeters) containing refuse and, so, depart from landfill conditions to varying degrees. Water was added in abnormal amounts in some cases, and had the effect of promoting methane formation. Data from such tests are among the best sources for estimating production figures, howeever, and must be given considerable weight in assessing likely gas generation from landfills. None of the production data from these studies is based on total refuse decomposition nor total conceivable gas production from the refuse tested. Rather, the period of most active methane generation apparently was observed. In most cases the production rates had dropped off, but not virtually ceased by the conclusion of monitoring. The different amounts of gas produced in the five studies most likely are due to differences in conditions in the lysimeters, such as moisture content, moisture flow, temperature, and other variables. Entry 17, in particular, was carried out over a relatively short period of time and conditions in the lysimeter including temperature and pH were not conducive to methane formation. Such factors undoubtedly caused the low generation figure, which is lower than that to be expected from full-scale landfills under reasonable conditions. Adverse conditions and difficulties in simulating landfill conditions are likely to be responsible for the very low figure of entry 19 as well. The 0.013 to 0.038 std cu m/kg (0.2 to 0.6 std cu ft/lb) range of entries 15 and 18 is likely to be closest of the five tests to actual gas production from a landfill in a humid climate. Note further that this quantity corresponds well with other practical values in Table 4.

Gas Composition

Gas composition data is much easier to determine and is, therefore, more readily available than is data on total gas production. Data nevertheless vary widely and gas composition in landfills has been recorded from 0 to 70 percent methane and from 0 to 90 percent carbon dioxide. Aerobic decomposition should produce a number of moles of carbon dioxide equal to the number of moles of oxygen consumed, so theoretically, any carbon dioxide concentration higher than 20 percent indicates that processes other than aerobic decomposition are involved. However, carbon dioxide concentrations less than 20 percent do not necessarily indicate that only aerobic decomposition is occurring because of the high solubility of carbon dioxide in water which lowers the carbon dioxide concentration in the gas as more moisture is added.

Facultative anaerobic decomposition produces the maximum carbon dioxide concentration and values up to 90 percent have been recorded.[32] Once the methane formation stage of decomposition is attained, carbon dioxide concentrations range generally from 40 to 50 percent. The exact value depends on the composition of the refuse being decomposed at that time; the amount, movement and chemical characteristics of moisture which influence the amount of carbon dioxide dissolved; and the rate of decomposition. A value of 45 percent is typical for full-scale actively decomposing landfills.

The methane concentration is affected more strongly by particular landfill characteristics than is the carbon dioxide concentration, reflecting the narrow range of landfill conditions suitable to methane formers.[8] The methane concentration is normally within the 45 to 65 percent range, with the most common values generally in the 45 to 55 percent range. Assuming active methane formation, properly balanced with associated acid formers, variations in methane concentration are caused by the specific composition of the waste, the components being degraded at a particular time, and by variations in carbon dioxide solubility noted previously. If improper balance is achieved between the methane and acid formers, the methane concentration will be lowered, other factors being equal. The importance of waste composition is illustrated by substituting the elemental analyses of the paper and fat fractions found in Table 3 into the overall equations for methanogenic decomposition. This indicates that the gas produced from paper degradation will be basically 51 percent methane and 49 percent carbon dioxide, whereas, from fats the gas composition will be 71 percent methane and 29 percent carbon dioxide.

It is important to review some of the reasons why a given landfill may depart from the typical gas production and composition figures shown in Tables 3 and 4. Overall waste composition is an obvious consideration and the composition of the matter decomposing at a particular point in space and time determines the gas generation rate and composition at that point.

Methane formation does not occur over the entire period of decomposition in a landfill; therefore, conditions limiting or precluding stable methane formation at any time throughout a landfill's history until complete stabilization has occurred will affect gas production directly.

There are further differences on a micro scale within a landfill. Due to particle size and composition differences, uneven moisture distribution, uneven oxygen distribution, uneven nutrient distribution, uneven pH and redox potential levels from point to point, etc., there will be major differences in gas generation from point to point within a landfill at a given time. Gas measurements are basically macroscopic in nature so the observer measures total gas generation which is the sum of production from each different pocket of activity within the landfill. Undoubtedly, the relative importance of methanogenic versus facultative versus aerobic decomposition pockets is a dynamic situation, changing as waste materials decompose and as environmental conditions vary on a micro scale.

Moisture content appears to be a major factor affecting methane production. Generally, methane formers function better as the moisture content increases, being very effective when completely submerged in water, as in a sewage sludge digester. This may be a result of improved uniformity of composition and reduced variations in nutrient availability, pH, concentrations of deleterious substances, etc. Increased moisture content also limits the accessibility of oxygen, which would poison the methane formation process if allowed to enter the landfill. Merz found moisture content to be the most important factor of those he studied affecting gas generation.[27] Merz and Stone found reduced production of methane in test, pilot scale landfills of less than 100 percent dry weight or 50 percent wet weight moisture content.[33]

The effect of low moisture content in limiting methane formation was substantiated by Merz and Stone using an enclosed lysimeter.[28] A moisture content of 50 percent dry weight or 34 percent wet weight was apparently too low to promote methane formation; whereas, a level of 65 percent dry or 40 percent wet weight was adequate once reasonable temperatures were achieved. The lack of methane formation at a moisture content of 43 percent dry or 30 percent wet weight in a study by Ramaswamy lends credence to this conclusion.[10] It is clear that moisture content is an important factor that can severely limit or promote methane production, depending on whether it is less than 50 percent dry weight or approaching 100 percent moisture dry weight, respectively. In dry climates in particular, this factor may limit the feasibility of methane extraction unless moisture is added to the refuse both prior to and during gas production.

Temperature is another major variable affecting methane generation. Anaerobic sewage sludge digestion is reported to be optimized at 35° C (95° F), with steadily decreasing levels of activity as the temperature drops to approximately 10° C at which point little or no methane generation occurs. Merz and Stone found that the temperature in small test landfills affected gas production with optimum temperatures also in the 30 to 40° C range.[33] Since landfill temperatures are often considerably less than 35° C, optimum conditions for methane formation frequently do not exist, and faculative micro-organisms will be favored. This affects both the total generation of methane and gas composition.

Procedural problems in measuring gas composition should also be mentioned. Air leaks along the walls of gas sampling probes are common problems allowing rapid contamination of landfill gas by air during gas sampling by suction. Use of clay or concrete seals, for example, reduces the leakage problem, but leaks through a cracked clay seal if drying takes place, or leaks around a clay or concrete seal as waste decomposes, settles and pulls away from the seal can continue to be problems. Settling of a landfill and changing moisture conditions at the surface of a landfill can allow air intrusion through the cover soil during sampling. Permeability of cover soil to gas flow varies widely as the moisture content changes or if freezing occurs.[35] The result may be variations in measured gas composition as a function of precipitation and temperature above the landfill. Further, changes in barometric pressure have apparently caused variations in gas composition, presumably removing landfill gases more rapidly during periods of low atmospheric pressure and retarding gas venting from a landfill during high pressure contitions.[2] Additional problems have been caused by the difficulty in obtaining good impermeable-gas container sealants and avoiding contamination of samples once taken from the landfill.[30] Some, but not all, gas composition data can be improved by mathematically removing a quantity of air associated with measured amounts of oxygen, and adjusting the percentage composition of the remaining gas accordingly. However, the difficulty with this type of correction is that oxygen may be naturally present in the landfill gas which would make the result erroneous.

Additional variables affecting methane generation were discussed above and will not be repeated here except to note the uniformity of the levels of these variables is of major importance. For example, for a landfill with favorable composition, temperature, and moisture content, the uneven distribution of decomposable nutrient or toxic substances, uneven distribution of acidic or basic pH conditions or the local accessibility to oxygen or other causes of increased redox potential which upset the ability of local portions of the landfill to sustain methane formation, may affect total methane production. However, adverse moisture content and temperature more than any other factors are felt to be the major reasons why some landfills exhibit reduced methane generation.

GAS PRODUCTION RATES AND DURATION OF GAS PRODUCTION

The wide range in types of decomposable matter present in solid waste suggests that no simple equation or rate constant can describe adequately the rate of decomposition or the rate of methane generation for a landfill. Readily decomposable substances like sugars and starches, for example, require less time to decompose than only moderately decomposable materials such as cellulose. In order to provide predictive capabilities for the rate of decomposition, it is useful to consider a landfill as a whole using sufficient measurements to describe the decomposition process, however complex, and apply the results to new landfills. Such an analysis may be based on knowledge of the composition characteristics of the various components in a landfill.

It is generally assumed that biological decomposition proceeds according to one of the following three equations:

$$(1) \quad -\frac{dc}{dt} = k$$

$$(2) \quad -\frac{dc}{dt} = kc$$

$$(3) \quad -\frac{dc}{dt} = kc^2$$

where "c" is the concentration of decomposable matter remaining at time "t", and "k" is a constant. Equation (1) describes a zero order reaction in which the reaction rate is independent of the concentration of substrate remaining to be decomposed. It is valid when factors other than substrate availability limit the rate of decomposition and frequently implies unfavorable or less than optimal conditions. For example, the presence of toxic substances, the lack of sufficient nutrients, or the lack of moisture may impede or control the rate of decomposition sufficiently that the concentration of substance remaining is unimportant. Similarly, so much decomposable matter may be present that other factors limit biological activity. Zero order kinetics often describes a transient situation; once the substrate concentration is in balance with other decomposition variables, it will become important. Another situation in which zero order kinetics is observed is when intermediate stages of decomposition exist, and the concentration of an interim substance may be controlling the overall reaction rate. In this case one is modeling the reaction rate on the wrong substrate. In general, if decomposition proceeds according to zero order kinetics, further investigation is suggested because it may be a result of inadequate understanding of the process, a serious process imbalance, or poor bacterial growth conditions. In similar fashion, second or higher order reaction rates indicate a major dependence on substrate concentration. Second or higher order rates imply that growth conditions are favorable, at least for decomposition of the substrate being modeled, and it is availability of substrate which is strongly controlling decomposition rates. It may be perfectly acceptable for the particular reaction being modeled to be of second or even higher order, but it does suggest that further information would be useful to try to explain the major dependence on substrate concentration.

The first order reaction rate is the most common. Simply stated it means that if the concentration of substrate is halved, its rate of destruction is also halved. It implies an adequate environment for decomposition to take place, capable of supporting more or less activity in accordance with substrate availability. Because of the difficulty in monitoring landfill decomposition, there is little evidence that decomposition of landfills proceeds according to first or any other order kinetic expression. Experience with other decomposition processes, however, such as anaerobic sewage sludge digestion, aerobic decomposition of decomposable organics (e.g., the BOD curve) and the like, indicate that the first order expression is common and is, therefore, worth attempting with landfills. Substrate concentration is readily controlled in a sewage sludge digester and the degree of mixing and presence of adequate water distributes the decomposition activity throughout the entire vessel. Conversely, with a landfill, pockets of widely differing characteristics promote different types and rates of decomposition, making it very difficult to apply any kinetic expression except a gross expression summarizing general observations of the landfill as a whole. Sampling problems, changing environmental conditions, mixture of substrates, and the impracticality of observing a landfill over its entire decomposition period makes it difficult to develop a more refined model.

Using the first order expression:

$$\frac{dc}{dt} = -kc$$

and integrating, where $c = c_o$ at $t = o$:

$$c_t = c_o e^{-kt}$$

and defining the half-life as the time "t_h" at which half of the original substance has been decomposed:

$$e^{-kt_h} = 1/2$$

or

$$t_h = \frac{0.69}{k}$$

Therefore, either the half-life or the rate constant "k" is all that must be specified to describe the decomposition of a material of known initial concentration c_o. Note that "c" may be a concentration of substances to be decomposed, such as organic matter, organic carbon, etc., or it may be a measure of the decomposition products, such as cubic meters (cubic feet) gas generated per kilogram (pound) refuse.

Since refuse contains materials of such widely differing characteristic rates of decomposition, it is logical to attempt to consider each individual component separately, using the first order kinetic expression and appropriate "k" or "t_h" values to describe its decomposition independent of the other components. The total landfill decomposition is then described by summing the decomposition of all of the components of interest. If one models gas generation, the expression would be:

$$\frac{dG}{dt} = \sum_{i=1}^{j} k_i c_i$$

where "G" is the rate of gas generation at time "t", and "j" is the number of identifiable components whose decomposition results in gas generation. The constant "k" becomes more complex in this expression because, as written, it must also include an efficiency term which relates the amount of gas generated to the amount of each waste component decomposed.

Table 3 indicates the typical amounts found of major readily identifiable components of refuse. Using these data, the organic portion of municipal wastes can be divided into three categories grossly described as: readily decomposable, moderately decomposable, and non-decomposable. Food wastes are readily decomposable, constitute 12 percent of the wet weight of refuse (Table 3), and in the absence of specific data may be assumed to have a half-life of one year. This value is reasonable and reflects the non-optimal conditions that exist in a landfill as well as the experiences of those who have researched refuse decomposition in older landfills in humid climates. Similarly, paper, wood, grass, brush, greens, and leaves may be considered moderately decomposable, comprise 57.2 percent of the refuse on a wet weight basis, and may be assumed to have a half-life of 15 years. Other organic materials, such as plastics, leather and rubber are assumed to be nondegradable. Using the overall formula for gas generation for each component (paper, grass, fats, etc.) of interest in Table 3, the moderately decomposable portion will produce ultimately 0.37 std cu m/kg (5.9 std cu ft/lb) wet refuse which will be 51 percent methane, and the readily decomposable portion will produce 0.06 std cu m/kg (9.94 std cu ft/lb) wet refuse, which will be 64 percent methane. These totals can be pro-rated over the life of the decomposition process using the assumed half-life values and assuming first order kinetics. Once again, the latter assumption derives from the common use of the first order equation in sewage sludge digestion and the lack of any substantive reason to not use it in landfills. The result is presented in Figures 1 and 2, in which the predicted percent of non-decomposable matter remaining and the cumulative amount of methane generated respectively, are shown as functions of time.

In addition to the assumptions and errors associated with use of the equation for calculating ultimate potential gas generation, discussed previously, the above simple approach assumes that a first order kinetic expression is valid, and that the refuse components can be divided into readily and moderately decomposable fractions with the assumed half-lives. The generation rate calculated represents a likely maximum value which may be considerably in error especially in the early years of a landfill decomposition. One modification of the basic method presented is to assume a rate of attainment of predominantly methane forming conditions to describe the early transition of a landfill from aerobic to facultative and finally to methanogenic decomposition. Such an approach was used by Bowerman.[3] This reduces the effect of initial portions of the curve of Figure 2 in which very high methane generation rates are shown to more realistic levels.

There are other ways by which the rate of gas production may be estimated. For example, the shapes of the curves describing gas production with time measured during digestion of sewage sludge in a 1932 work by Fair and Moore[25] were used to modify the mathematical expression used in the previous example. Depicted in Figure 3 is the curve developed by Fair and Moore (rendered dimensionless both with respect to time and rate of gas production) and assuming half-lives for various components of refuse to provide a time basis for a gas generation curve describing the subject landfill. They used existing data on gas generation rate for a known portion of the landfill over a one year period to set the vertical scale on the gas generation curve

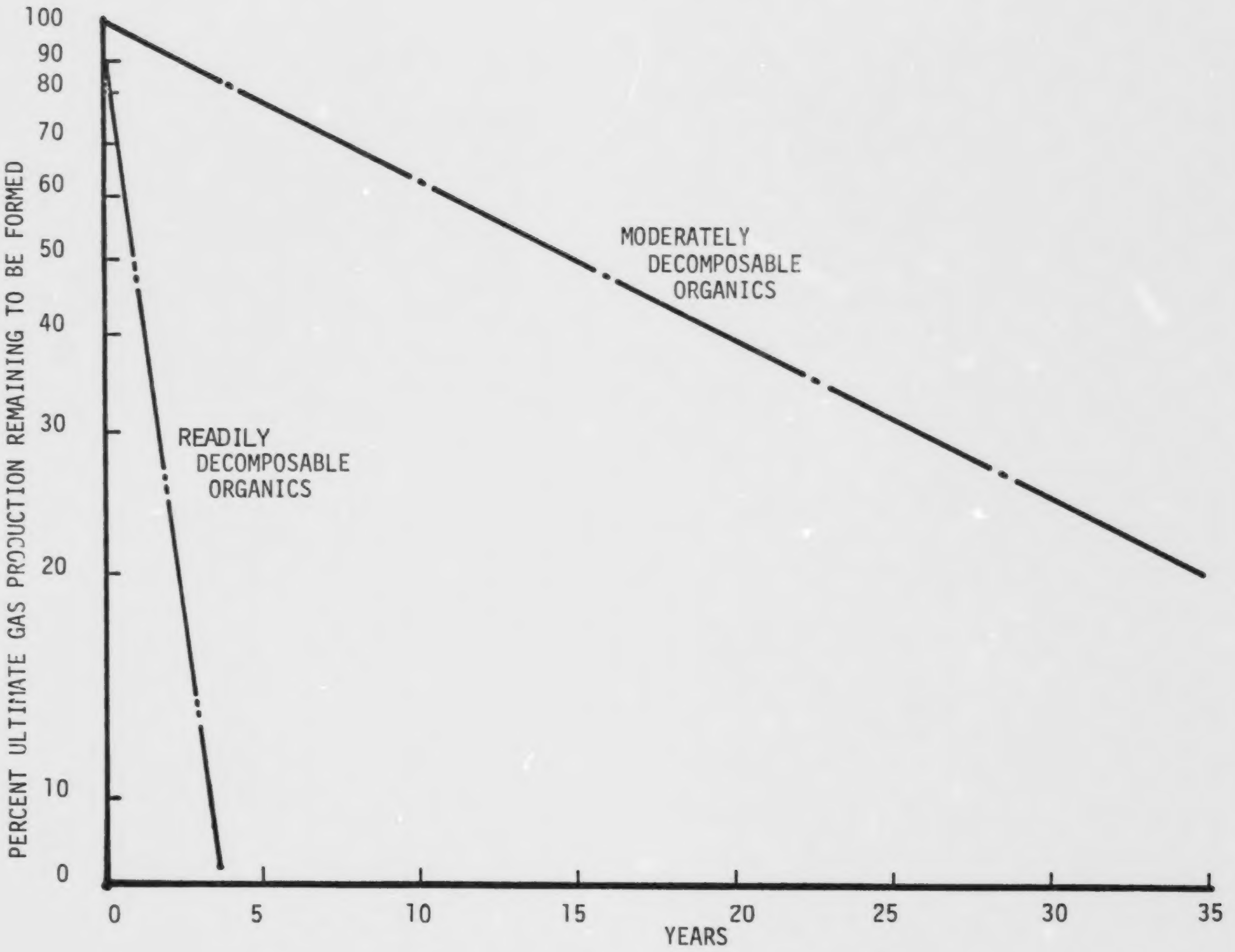


Figure 1. Theoretical gas production remaining as a function of time.

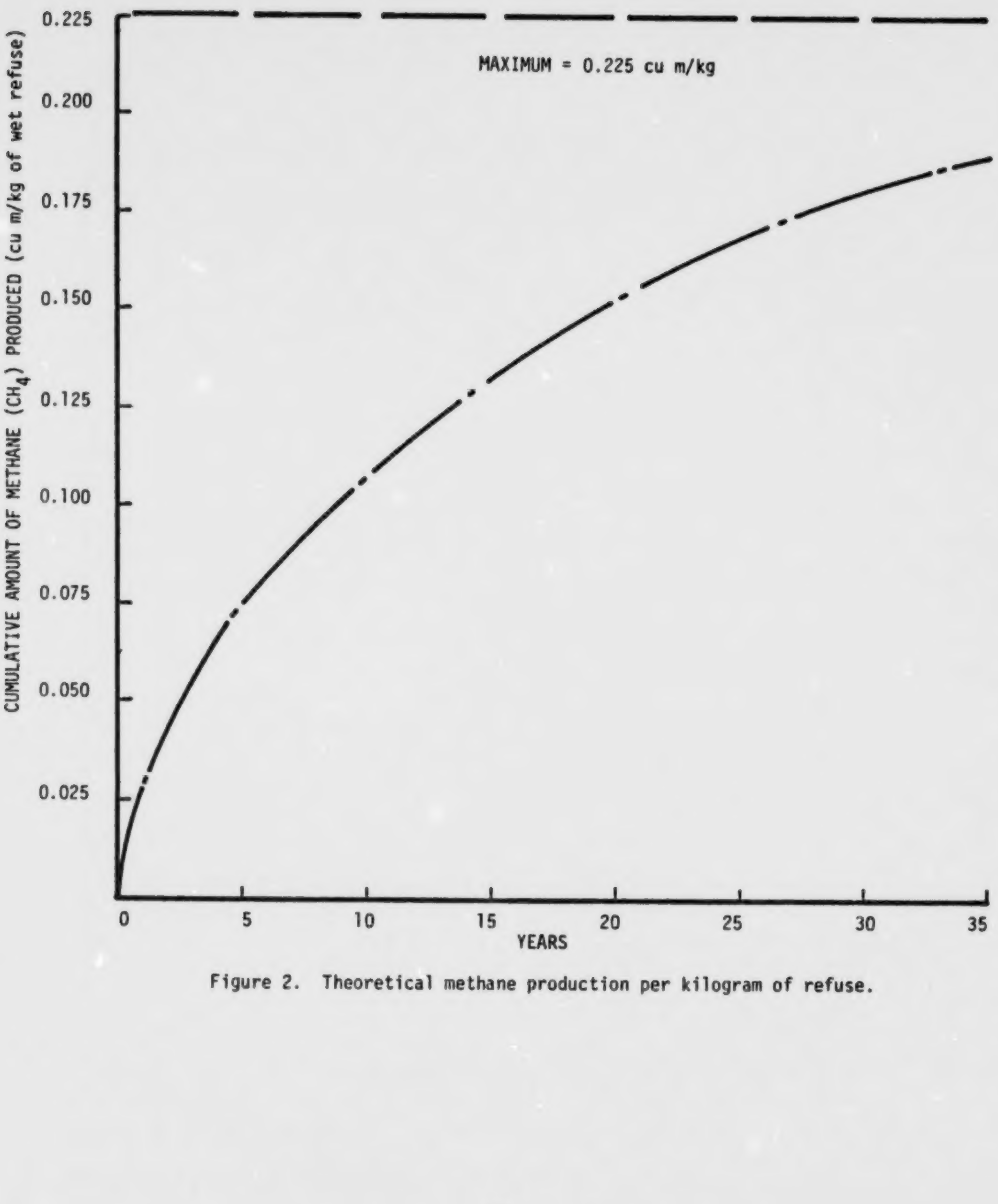


Figure 2. Theoretical methane production per kilogram of refuse.

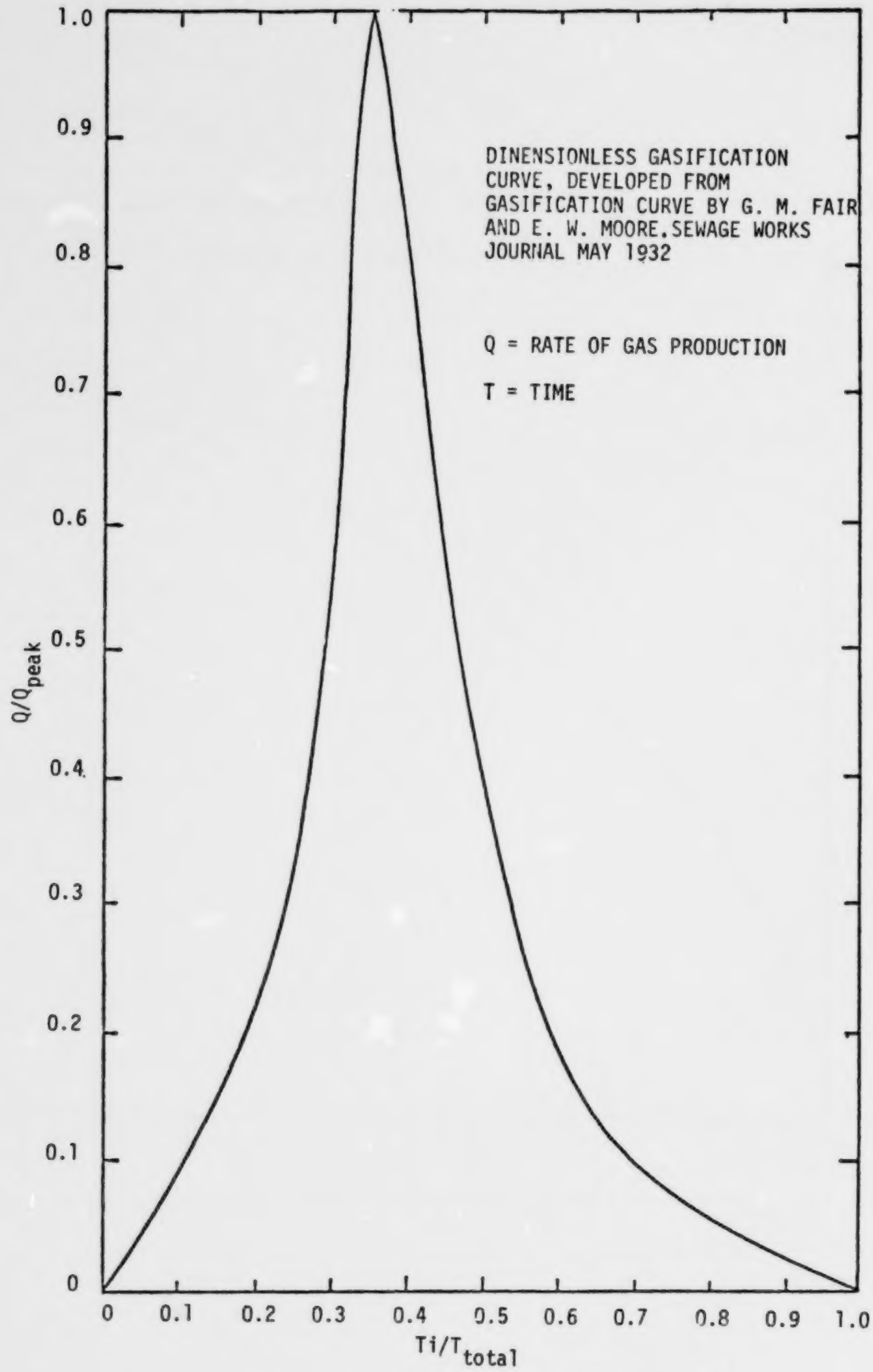


Figure 3. Dimensionless gasification curve.

mentioned previously. The result was a gas production curve based on the shape of the Fair and Moore curve for each group of refuse components assumed to decompose simultaneously. The curves were then summed to give the total gas generation as a function of time.

The selection of half-lives is little more than a guess based on some experience with sewage sludge digestion. Values ranging from one-half to ten years for readily decomposable materials and two to 25 years for moderately decomposable materials have been used.[3,18,25] Some investigators assume that refractory materials such as plastics result in no methane formation; others assumed half-lives as low as 20 years. Climatic conditions which in turn affect the kinetics of gas formation should be considered in estimating half-lives in the absence of data.

Table 5 summarizes some of the gas generation rates found in the literature. Attempts have been made in each case to put the entries on the same basis to make them comparable, but this is difficult because of conditions peculiar to each entry. Nevertheless, an idea of typical projected or measured rates may be obtained from Table 5. Except in the case of closed lysimeters, it is clear that gas production figures cannot be based on direct total measurement. Several cases exist, however, in which some degree of landfill testing was used as a basis of extrapolating the data over the entire landfill over a longer period of time than was actually monitored, or both. The term "measured" is used in Table 5 to separate estimates based on measurements from those based on purely theoretical grounds. Similarly, values based on literature review involving unknown or no measurements are listed as "estimated".

Entries 1 through 4 of Table 5 are typical of the purely theoretical (entry 1) and literature review and experience (entries 2, 3, and 4) approaches to the rate of gas generation. It is interesting that the theoretical result is much closer to a realistic value than the theoretical estimate of total gas production shown in Table 4. Part of this is the choice of five years after landfilling as the time at which the generation rate was calculated from Figure 2 for entry in Table 4. It is clear from the shape of the curve that much higher or lower rates could have been calculated had the landfill age been more or less, respectively. However, five years was selected as being representative of the ages of full-scale landfills tested. More important, however, is the probability that a landfill is actually undergoing methanogenic decomposition at this age, thereby following the theoretical predictions more closely. At earlier ages the theoretical model overpredicts because of the time necessary to achieve stable methane formation in an actual landfill. Since significant amounts of gas are predicted theoretically during the initial years but probably not produced in reality, part of the discrepancy in total production is explained. No data are available on gas production from landfills significantly older than 20 years, so comparisons of actual to theoretical rates cannot be made.

Entries 5 through 11 are basically results from enclosed lysimeters or test landfills. Consequently, measurements of gas production should be reasonable; subject to sampling and analysis difficulties, leaks, and the like.

TABLE 5. LANDFILL GAS (CARBON DIOXIDE AND METHANE) GENERATION RATE FROM MUNICIPAL SOLID WASTE

Sources	Conditions	Basis	Gas production rate refuse as received std cu m/kg
1. This report, Figure 2	After 5 years in landfill	Theoretical	0.016
2. Bowerman, et al (3)	Literature and various data sources	Estimated	0.014
3. SCS Engineers (37)	Literature and various data sources	Estimated	0.004 to 0.014
4. Boyle (13)	Literature	Estimated	0.004 to 0.014
5. Merz & Stone (28)	Lysimeter, calculated from 300 days CH_4 production	Measurement	0.005
6. Streng (30)	Ave. range during active CH_4 prod. for solid waste only lysimeter	Measurement	0.005 to 0.006
7. Chian & DeWalle (31)	Lysimeter gas prod. over 300 days, recalculated for cell 4*	Measurement	0.0002
8. Rovers & Farquhar (29)	Lysimeter, maximum production rate observed	Measurement	0.008
9. Merz (27)	Maximum production in lysimeter at "optimal" temp. and percent H_2O	Measurement	0.032
10. Ramaswamy (10)	Lysimeter with unusually high food waste content	Measurement	0.400
11. Beluche (32)	Cited in (25)	Measurement	0.003
12. Bishop (38)	Pilot-scale landfill, low H_2O content	Measurement	0.032 to 0.063

(continued)

TABLE 5 (continued)

	Sources	Conditions	Basis	Gas production rate refuse as received std cu m/kg
13.	Engineering Science (39)	Test landfill, maximum and minimum observed production on per year basis over 3-years monitoring	Measurement	0.016 to 0.041
14.	Carlson, E.L. (35)	Estimated during landfill pump tests, varies seasonally	Measurement	0.004 to 0.039
15.	Carlson, J.A. (2)	Estimated during landfill pump tests, both values given	Measurement	0.021 to 0.029
16.	City of Los Angeles (25)	Theoretical extrapolation of short-term landfill pumping data	Measurement/ Theoretical	0.011
17.	City of Glendale (40)	Testing of landfill, recalculated for 53 percent CH_4	Measurement	0.002

* Corrected to refuse composition of Table 3.

It is very difficult, however, to achieve realistic conditions in a test landfill as mentioned previously. Moisture routing is one particularly difficult aspect to model of a full-scale landfill. Entries 6, 7, and 8 experienced difficulties attaining methane formation and traced problems to moisture, temperature, air leaks, and acidic pH conditions. In some cases, methane formation was never achieved and in others low levels were observed. More time might have allowed methane formation to develop in some of these cases. At any rate, the rates of production for many of these entries are likely to be unrealistically low. Similarly, entry 10 is abnormally high because of a waste artificially high in methane formation potential. Entries 5 and 9 indicate the effect of moisture content with higher production rates associated with wetter landfills.

Entries 12 and 13 are on pilot-scale landfills and are thought to be reasonable results for young, actively decomposing landfills.

Entries 14 through 17 are for full-scale landfills. The typical approach for such studies is to pump gas out of a perforated pipe placed in a well in the landfill which is backfilled with gravel. The well hole is typically 0.91 to 1.22 m (36 to 48 in.) in diameter. The area of influence of each gas withdrawal well is then determined by pumping the gases and monitoring changes in pressure at a series of test probes located at various distances from the withdrawal well. The test probes are basically pipes, perforated along the bottom several feet, embedded in the landfill to allow measurement of pressure. While it is possible to measure with reasonable accuracy the rate of gas withdrawal and its composition, it is much more difficult to define the radius of influence so that the gas production can be related to the correct volume of refuse. Consequently, the production rates given in these entries are subject to errors in tonnage of refuse generating gas measured, gas losses to other parts of the landfill or through cover or surrounding soils, and whether the value applies to only that portion of the landfill tested at that time. Entry 16 is especially interesting, because the value is based on a year of pumping from a series of withdrawal wells.

The values given in Table 5 suggest that both from test and full-scale landfill data, a reasonable rate of total gas generation is 0.006 to 0.038 std cu m/kg/yr (0.1 to 0.6 std cu ft/lb/yr) for refuse as received. The range is explained in part by seasonal or climatic variations relating primarily to moisture content and to a lesser extent, temperature variations. Values outside this range are generally explainable by unusual refuse composition, lack of formation of a mature methanogenic decomposition process, or very dry refuse.

The period over which methane is produced is unknown. Theoretically, decomposable matter will degrade in a landfill for an infinite period, but obviously a point will be reached in practice when so little decomposition takes place that methane production effectively ceases. At this point, facultative biological, chemical and physical decomposition as well as some traces of methanogenic decomposition, will continue at some low level until the refuse is, for all practical purposes fully decomposed. All of the studies cited in Table 5 cover such a short period of time that little can be said regarding the period of methane production. Several of the lysimeter and test landfill studies did apparently extend over the period of active methane production rates or were declining or had stopped altogether by the end of the monitoring period. Such studies, however, are probably not representative of full-scale landfills where methane generation appears to occur over periods much longer than those monitored for the lysimeter or test landfill studies. Those entries which project methane production over a period of time (e.g., entries 2, 15, 16, and 17) generally assume a period of active methane production on the order of ten years (at rates warranting collection).

Factors affecting gas generation rates (as opposed to total production per unit weight of refuse) have been clearly identified in the literature although in some particular test landfills or lysimeters, the effects of these factors are obscured by other factors which were apparently controlling. The effect of temperature has been shown in several studies and is summarized in reference 36. The optimum temperature range for mesophilic anaerobic bacteria is 30 to 40° C which has been observed to give maximum gas production rates. Moisture content is apparently the major variable affecting gas production rates, assuming that reasonable environmental conditions supportive of methane formation exist. Reference 36 also summarizes data from several sources indicating a general improvement in gas production with increasing moisture content ranging up to complete water submersion in refuse digestors. Moisture content significantly less than 50 percent on a dry weight basis (34 percent wet weight) may limit gas production. However, there is considerable uncertainty on this value because landfills with measured moisture content as low as 15 to 20 percent (wet weight basis) are producing methane at relatively high rates. Certainly, higher moisture content will sustain higher gas production rates but other variables in general and temperature in particular then play an increasingly major role.[10,28]

SUMMARY

Gas production in decomposing landfills is complex, involving availability of balanced supplies of decomposable solid waste components plus satisfaction of stringent environmental requirements to promote growth of methane forming bacteria. Non-methanogenic decomposition processes, favored initially upon refuse placement in a landfill and during subsequent years when environmental factors upset stable methane formation, make it difficult to predict accurately methane production quantities and rates.[41] Knowledge of the specific requirements of methane formers exists, however, and has been used successfully to interpret available gas production data. Such knowledge stems primarily from experience with sewage sludge digestion.

The theoretical amount of gas generated from typical residential/commercial/and light industrial solid waste is 0.45 std cu m/kJ (7.2 std cu ft/lb) of wet (as received) waste. It would have a composition of 54 percent methane and 46 percent carbon dioxide by volume. Based on lysimeter and full-scale landfill tests, however, a value of 0.013 to 0.047 std cu m (0.2 to 0.75 std cu ft) of methane/kg (lb) is more realistic. The rate of methane generation is also subject to considerable errors in estimation, with a reasonable theoretical value of 0.008 std cu m (0.13 std cu ft) of methane/kg (lb) of refuse per year after five years in a landfill Averaging the results of lysimeter and full-scale landfill measurements, total gas generation is in the range of 0.006 to 0.038 std cu m/kg/yr (0.1 to 0.6 std cu ft/lb/yr) over the period of most active methane formation, which is typically assumed to occur during the first five years or so after landfilling. It is difficult to reconcile these results with the beliefs of many researchers that the economically productive period of a landfill may last anywhere from 15 to 25 years.

Factors which appear to regulate methane generation most often are moisture content and temperature. A refuse moisture content on the order of 50 percent on a dry weight basis and preferably 100 percent (34 and 50 percent wet weight) is required for active methane generation. Likewise, a temperature of less than 15° C (59° F) appears to severely limit methane generation with the rate of generation increasing with increasing temperatures up to an optimal temperature of 30 to 40° C (86 to 104° F). It is likely that sub-optimal temperature and moisture levels are the most common causes of retarded methane generation in full-scale landfills. Since methane is routinely found in decomposing landfills, sub-optimal conditions seldom preclude all traces of methane formation. Rather, when such conditions exist they serve to limit the rate of generation and so might conceivably be controlled to speed up the generation process.

SECTION 5

LANDFILL GAS UTILIZATION ALTERNATIVES

Possible uses for landfill gas are presented in this section, together with technical and economic analyses of process systems required to prepare the landfill (methane) gas for use. The analyses are based on landfill gas of typical composition, although it must be noted that gas composition varies somewhat depending on the composition of the solid waste, the age or maturity of the landfill and other factors.

Each economic analysis determined the approximate gas quantity required to render each alternative economically viable. The assessment considered the number of years required to "payback" the original capital investment, mindful of the number of years that a typical landfill can be expected to produce gas at a rate sufficient to permit economical recovery.

LANDFILL GAS COMPOSITION

Landfill decomposition gases are comprised almost entirely of methane and carbon dioxide in about a 1:1 ratio. The ratio of methane to carbon dioxode varies somewhat due to the type, age, condition and mix of organic components present. However, gas composition tends to remain relatively constant during the useful period of gas production varying slightly from landfill to landfill and over time.

Nitrogen and oxygen are normally the next most abundant constituents in landfill gas. These gases occur primarily as a result of air being trapped as the waste is deposited or suction due to negative internal pressure as the landfill gas is extracted. The latter is minimized with proper well design, gas extraction and selection of landfill cover material. Because oxygen can be consumed within the landfill by faculative or aerobic bacteria or in chemical reactions with materials present (e.g., metals), the ratio of nitrogen to oxygen will not always be 4:1 and it is not possible to identify that portion of the nitrogen or oxygen in a sample that is due to ingested air and that portion that is part of the gas produced. In samples taken using techniques that virtually eliminate the possibility of air ingestion, nitrogen is present in more than trace amounts. The production of nitrogen conceivably could occur as a result of waste decomposition, since a small amount of nitrogen generally is present in typical landfill gas.

Of the many substances that are found in landfill gas in concentrations less than 1 percent, hydrogen, hydrogen sulfide, carbon monoxide and higher-order hydrocarbons are the most abundant. Although these compounds normally comprise only a few hundred parts per million (ppm), some analyses show them occurring as several thousand ppm (one thousand ppm is equal to 0.1 percent volume). Hydrogen sulfide, because of its unpleasant odor in gaseous form, toxicity, and corrosiveness when dissolved in water (sulfuric acid) is the most troublesome of these compounds.

Trace amounts (1 to 50 ppm) of numerous additional compounds have been reported in gas analyses performed by mass spectroscopy. These include sulfur dioxide, benzene, toluene, perchloroethylene, methyl chloride, and carbonyl sulfide. In addition, the moisture in the gas (most collected landfill gases are saturated or near saturation) has been found to contain droplets of numerous organic acids (carbonic, acetic, propionic, isobutyric, isovaleric, isocaproic, and others), ammonia and other less important compounds in trace quantities (less than 1.06 mg/cu m). Some of these compounds are of concern due to their corrosiveness, or tendency to plug up process equipment or interfere with process activities.

To provide the greatest applicability for the results of this study, a landfill gas that contained each of the compounds in the upper range of concentrations found was used for analysis purposes. This makes the results somewhat conservative because in most of the gas analyses reviewed, only a few of these compounds were found and their concentrations were near the lower end of the ranges. Thus, cost estimates affected by corrosion control requirements or similar measures needed to control adverse affects of these compounds tend to be overstated with respect to most landfill gases. A certain amount of air intrusion due to leaks in typical gas recovery systems was assumed, giving methane percentages resulting in a higher heating value (HHV) of 18289 kJ/std cu m (490 BTU/scf). A more conservative figure of 17727 kJ/std cu m (475 BTU/scf) has been used in subsequent calculations.

Typical gas composition used in this study is listed in Table 6.

ALTERNATIVE LANDFILL GAS USES

Based on the typical landfill gas composition listed in Table 7, potential uses are of two basic types:

- o Use as a fuel gas at various quality levels
- o Use as a process feed stock

Table 7 lists alternative applications of landfill gas as a fuel at various quality levels.

Conversion of methanol is a representative process using landfill gas as the feed stock. Other potential conversion products include ammonia and urea. However, methanol conversion is perhaps the most feasible of the three possibilities mentioned. More suitable feed stocks are available in relatively larger quantities such that considering the economies of scale, use of landfill gas as a feed stock from a single site would have basic cost disadvantages. The methanol process is treated in the economic analysis to

TABLE 6. TYPICAL LANDFILL GAS COMPOSITION AND CHARACTERISTICS

Component	Component percent (dry volume basis)
Methane	47.5
Carbon Dioxide	47.0
Nitrogen	3.7
Oxygen	0.8
Paraffin Hydrocarbons	0.1
Aromatic & Cylic Hydrocarbons	0.2
Hydrogen	0.1
Hydrogen Sulfide	0.01
Carbon Monoxide	0.1
Trace compounds*	0.5
Characteristic	Value
Temperature (at source)	41°C
High heating value	17727 kJ/std cu m†
Specific gravity	1.04
Moisture content	Saturated (trace compounds in moisture)‡

* Trace compounds include sulfur dioxide, benzene, toluene, methylene chloride, perchlorethylene, and carbonyl sulfide in concentrations up to 50 ppm.

† Landfill gas (as received) from Palos Verdes landfill has HHV of 21646 to 21832 kJ/std cu m (3). Landfill gas (as received) from a Mountain View landfill test well has a HHV of 16420 to 16794 kJ/std cu m with a 20-21 percent nitrogen content by volume (1, 2).

‡ Trace compounds include organic acids(7.06 mg/cu m) and ammonia (0.71 mg/cu m).

TABLE 7. ALTERNATIVE LANDFILL GAS FUEL APPLICATIONS

Application	Processing required	Higher heating value(HHV)* kJ/std cu m (BTU/scf)	Limitations
Direct Fuel	Condensate & particulate removal	17167 to 18287 (460 to 490)	Must be consumed at the landfill
Direct Fuel	Dehydration	17167 to 18287 (460 to 490)	Can be transported via pipeline moderate distances
Direct Fuel	Dehydration & partial carbon dioxide removal	24258 to 27990 (650 to 750)	can be transported moderate distances and mixed with natural gas at low ratios
Direct Fuel	Dehydration & total carbon dioxide removal	35080 to 35827 (940 to 960)	Can be mixed with natural gas at intermediate to high ratios
Direct Fuel	Dehydration, carbon dioxide & nitrogen removal	35827 to 36947 (960 to 990)†	Can be mixed with natural gas at intermediate to high ratios
Direct Fuel	Dehydration & carbon dioxide removal plus sweetening with approximately 1 percent propane	37320+ (1,000+)	Equivalent to natural gas

* 1 percent other hydrocarbons add about 1120 kJ/std cu m (30 BTU/scf) to HHV.

† Palos Verdes landfill molecular sieve product, during 204 days of operation, averaged 99 percent methane, HHV 36947 kJ/std cu m (990 BTU/scf) (3).

demonstrate this contention.

Direct fuel application with partial carbon dioxide removal offers no distinct advantage over use of gas that has only been dehydrated. The cost of removing all carbon dioxide is not that much greater than that of removing only about one-half. Also, for introduction into the natural gas distribution system, most utilities require a gas with a heating value of about 35454 kJ/std cu m (950 BTU/scf), so a gas with only part of the carbon dioxide removed cannot be used for this purpose. For these reasons, consideration of partial carbon dioxide removal was not carried further in the analysis. (Note that unique circumstances can render this approach feasible.)

Raw landfill gas can be consumed on or immediately adjacent to the landfill site to generate steam for process or heating use, or to generate electricity via a gas engine, gas turbine or steam turbine as the prime mover. The advantage of on-site utilization is that little or no processing is required. The gas can be used as a medium heating value fuel directly after passing through a condensate and particulate separator. These two raw gas utilizations are analyzed in greater detail.

ALTERNATIVE PROCESSES AND PRODUCTS

The most suitable utilization of gas from a given landfill site depends upon the quality of the raw gas recovered (primarily methane content and amount of nitrogen and oxygen), the demand for energy near the site and the quantity of gas recovered. Based on demonstration projects and the few additional commercial operations now in late stages of development, industry will purchase substandard fuel gas provided it does not damage existing facilities (pipelines, boilers and furnaces, etc.), or, if there is a need for low to medium pressure/temperature steam. Under some circumstances, industry also will purchase electricity. However, if there are no large industrial or institutional users of fuel gas, steam, or electricity near the landfill site, it probably will be necessary to sell upgraded gas or electricity generated on-site to the local utility. (In unusual cases, the only suitable alternative may be synthesis of methanol, ammonia or urea. However, the economics of these processes tend to require large landfill gas recovery rates in order for the facility to turn a profit.)

To cover the range of potential uses or products feasible under a variety of situations, representative alternative processes producing specific products were selected for analysis. The selection was based on current state-of-the-art and minimal technical risk processes. It was recognized that for some products (e.g., dehydrated and upgraded landfill gas) there are a variety of process techniques and adsorbant materials available. Thus, for example, use of substances such as mono-ethanol-amine (MEA) may be substituted for the molecular sieve technique to remove carbon dioxide in Alternatives II, III, and IV. The selections made were considered representative of the range of product qualities and processes attainable at this time.

The alternatives analyzed were:

I. Dehydration (dehydrate, compress and sell 17727 kJ/std cu m (475 BTU/scf) gas)

II. Upgrading (remove water and carbon dioxide, compress and sell 35454 kJ/std cu m (950 BTU/scf) gas).

III. Upgrading (remove water, carbon dioxide and nitrogen, compress and sell 36387 kJ/std cu m (975 BTU/scf) gas).

IV. Upgrading and Blending (remove water and carbon dioxide, add about 1 percent propane and sell 37320 kJ/std cu m (1000 BTU/scf) gas).

V. Steam generation (use raw gas to generate steam and sell steam)

VI. Electricity Generation (use raw gas to generate steam to drive steam turbine-generator and sell electricity)

VII. Electricity Generation (use raw gas in gas turbine-generator and sell electricity)

VIII. Electricity Generation (use raw gas in gas engine-generator and sell electricity)

IX. Methanol Synthesis (remove water and carbon dioxide, reform and convert to methanol, sell methanol)

Each alternative is briefly described using a simplified process schematic diagram. The following assumptions were used in evaluating each alternative:

1. Raw gas must be consumed on-site because moisture prevents pipeline transport
2. Dehydrated gas is supplied to large fuel gas users within approximately 8 km (5 miles) of the site
3. Steam is supplied to large users within 1.6 km (1 mile) of the site
4. Electricity is sold to one or a few users, or is synchronized and sold to the local electric power utility
5. Upgraded gas is sold to the local gas utility and methanol is sold to large users locally

Three alternative methods for generation of electricity were analyzed because it was anticipated that their economics as functions of capacity would be different, thus different methods might be applicable to small, medium and large gas quantities. The propane blending upgrade process was explored as a substitute for nitrogen removal via liquification which tends to be an expensive process.

Alternative I - Dehydration to Product 17727 kJ/std cu m (475 BTU/scf) Dry Gas

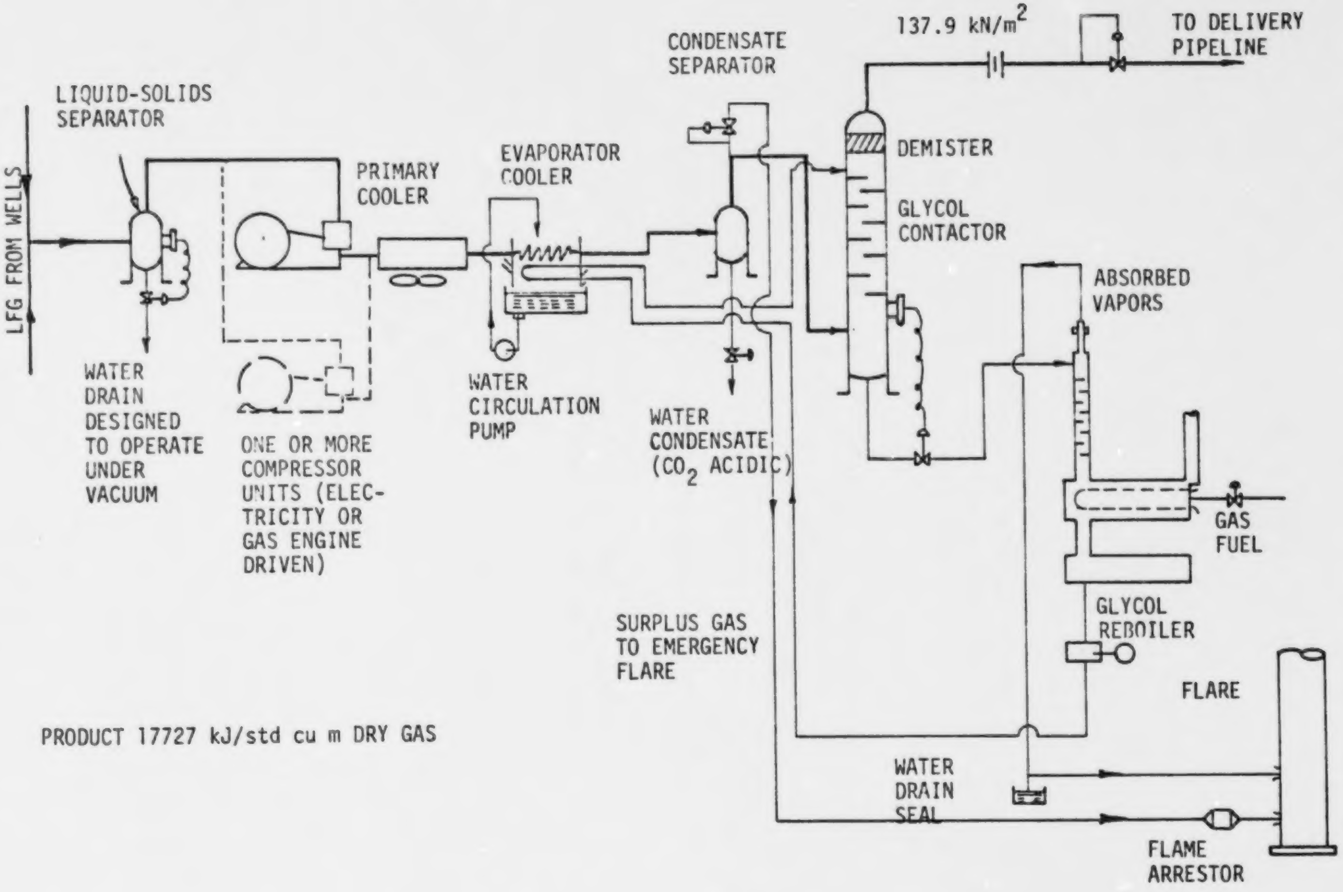
This is a basic process to remove water vapor from landfill gas for short to medium distance transport by pipeline to single or multiple fuel gas users. The raw landfill gas is recovered using the suction of the compressor(s) applied to the collection manifold. As shown in Figure 4, raw (as-recovered) gas is passed through a liquid-solids separator to remove condensate and any particulates present, then is compressed in a low pressure compressor followed by two stages of cooling and a condensate separ - tor, and then to a tri-ethylene-glycol dehydrator before passing to a delivery pipeline or to a second compression stage (not shown) depending upon pipeline length and user delivery pressure requirements. Rich glycol is circulated through a reboiler where the water is vaporized and the lean glycol recirculated and reused. The flare unit is normally used to destroy vapors eminating from the glycol reboiler and in an emergency situation, to flare the landfill gas.

Refrigeration dehydration can be substituted for the glycol unit for small gas quantities. The ratio of delivered gas to recovered gas ranges from 0.95 for low pressure, 153 kN/sq m (22.5 psig) delivery, using electric motor driven compressors to about 0.83 for medium pressure, 448 kN/sq m (65 psig) delivery, using gas engine driven compressors.

Alternative II - Upgrading to 35454 kJ/std cu m (950 BTU/scf) Gas

Depicted in Figure 5 is a basic landfill gas upgrading process incorporating removal of carbon dioxide as well as water vapor to achieve a dry gas heating value ranging from about 35080 to 35827 kJ/std cu m (940 to 960 BTU/scf) depending upon raw gas heating value (methane and other hydrocarbon content) and amount of carbon dioxide and nitrogen in the gas together with the effectiveness of the removal technique. Several carbon dioxide removal techniques are available including molecular sieve adsorption; or mono-ethanol-amine, hot potassium carbonate or polyethylene glycol water absorption. Based on data available on these alternative techniques, the molecular sieve was selected for analysis because it appeared to be the most economic. With this alternative, it is important not to over-pump the landfill since that increases the nitrogen content and reduces the heating value of the product. Nitrogen is not removed by these techniques and may decrease carbon dioxide removal effectiveness as well. Upgraded gas produced by molecular sieve separation normally would be suitable for commingling with natural gas at a reasonable ratio. For example a mix of 10 percent upgraded landfill gas with 90 percent 37320 kJ/std cu m (1000 BTU/scf) natural gas gives a mixed heating value of 37133 kJ/std cu m (995 BTU/scf), or a 2 percent mix results in a reduction of only 37.32 kJ/std cu m (1 BTU/scf) in heating value.

Two or three stages of compression are typically required before the upgraded gas can be introduced into the local utility natural gas main. Approximately 62 percent of the heating value of the input raw landfill gas will be contained in the output upgraded gas, the difference being used or


LFG FROM WELLS
LIQUID-SOLIDS SEPARATOR
WATER DRAIN DESIGNED TO OPERATE UNDER VACUUM
ONE OR MORE COMPRESSOR UNITS (ELECTRICITY OR GAS ENGINE DRIVEN)
PRIMARY COOLER
EVAPORATOR COOLER
WATER CIRCULATION PUMP
CONDENSATE SEPARATOR
WATER CONDENSATE (CO2 ACIDIC)
137.9 kN/m2
TO DELIVERY PIPELINE
DEMISTER
GLYCOL CONTACTOR
ABSORBED VAPORS
GAS FUEL
GLYCOL REBOILER
SURPLUS GAS TO EMERGENCY FLARE
FLARE
WATER DRAIN SEAL
FLAME ARRESTOR

PRODUCT 17727 kJ/std cu m DRY GAS

Figure 4. Alternative I - Dehydration to dry fuel gas.

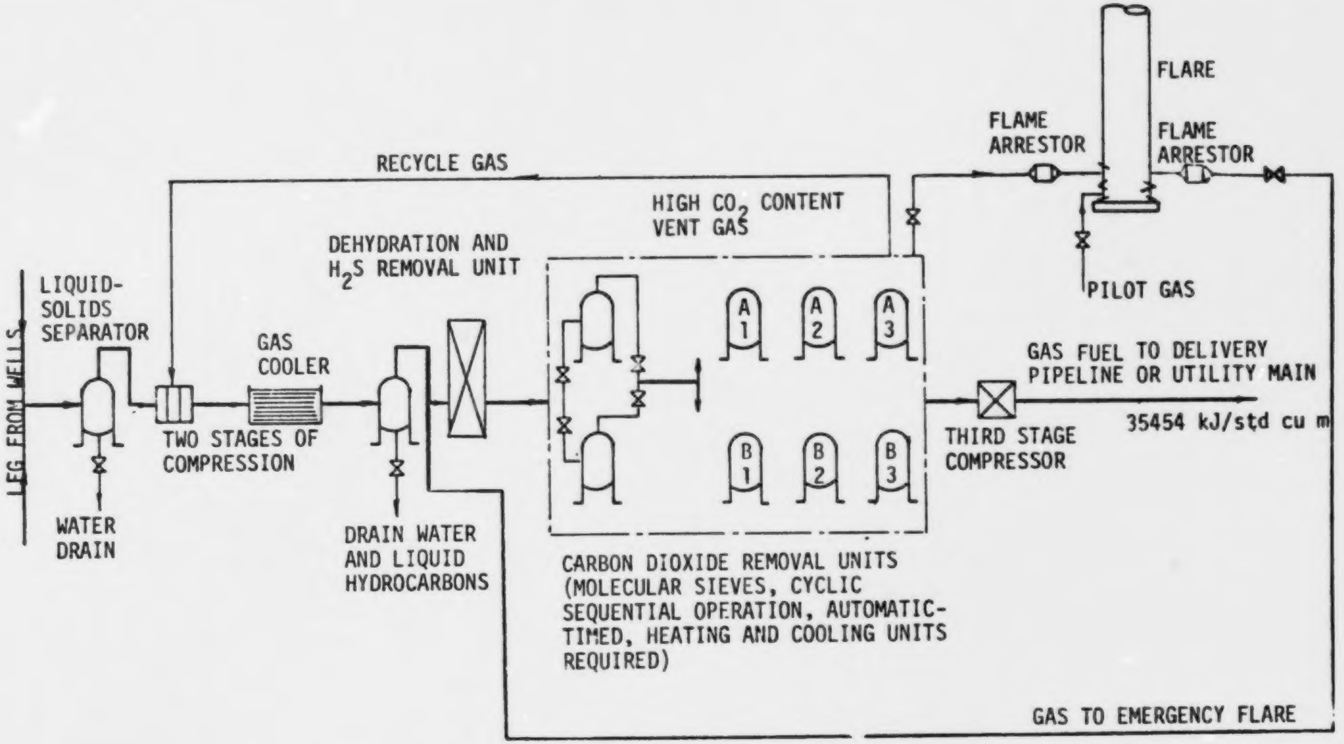

LEG FROM WELLS
LIQUID-SOLIDS SEPARATOR
WATER DRAIN
TWO STAGES OF COMPRESSION
GAS COOLER
RECYCLE GAS
DEHYDRATION AND H_2S REMOVAL UNIT
DRAIN WATER AND LIQUID HYDROCARBONS
HIGH CO_2 CONTENT VENT GAS
A 1
A 2
A 3
B 1
B 2
B 3
CARBON DIOXIDE REMOVAL UNITS (MOLECULAR SIEVES, CYCLIC SEQUENTIAL OPERATION, AUTOMATIC-TIMED, HEATING AND COOLING UNITS REQUIRED)
FLAME ARRESTOR
FLARE
FLAME ARRESTOR
PILOT GAS
GAS FUEL TO DELIVERY PIPELINE OR UTILITY MAIN
35454 kJ/std cu m
THIRD STAGE COMPRESSOR
GAS TO EMERGENCY FLARE

Figure 5. Alternative II - Upgrading to 35454 kJ/std cu m fuel gas.

lost in the upgrading process. Because of this energy loss, this alternative should be used only when there is no large fuel gas user in the vicinity of the landfill and the product gas must be sold to the local gas utility.

Alternative III - Upgrading to 36387 kJ/std cu m (975 BTU/scf) Gas

This alternative employs the same techniques used in Alternative II with the addition of nitrogen removal fractional liquification using mechanical refrigeration. This process liquifies the methane component of the gas leaving nitrogen and other impurities to be exhausted in gaseous form. Generally, it would be appropriate only when the nitrogen content of raw landfill gas is unusually high due to air intrusion into the landfill or extraction system. It requires considerable additional equipment for the liquification process and substantially increases the operating cost due to the high energy requirement of mechanical refrigeration. The basic process schematic is shown in Figure 6. Only about 54 percent of the energy content of the raw landfill gas is delivered in the methane product, the difference being used or lost in the total process.

Alternative IV - Upgrading and Blending with Propane

This alternative was explored as a substitute for Alternative III for applications where high BTU gas is required, essentially equivalent to natural gas or nearly pure methane. The schematic in Figure 7 shows only the process required to be added to the system of Alternative II which provides dehydration and carbon dioxide removal from raw landfill gas The blending of approximately 1 percent of propane to 35454 kJ/std cu m (950 BTU/scf) product of the initial two steps of the process increases the heating value to 37320 kJ/std cu m (1000 BTU/scf). Blending additional propane could increase the heating value further should this be necessary. The ratio of heating value in the product gas is the same as for Alternative II plus the propane added.

Alternative V - Steam Generation

This alternative depicted schematically in figure 8, utilizes an onsite boiler to generate low or medium pressure/temperature steam (ranging from 120°C (250°F) saturated to about 260°C (500°F), 3448 kN/sq m (500 psig) superheated steam) burning raw landfill gas that has passed through a liquid-solids separator and low pressure compressor. The compressor is used to apply a negative pressure to the collection manifold and for supplying landfill gas to the boiler burners at a pressure ranging from 34 to 69 kN/sq m (5 to 10 psig). To achieve maximum economy in water use, a condensate return line as well as an insulated steam delivery pipeline is needed between the boiler and the steam purchaser. Because of the high cost of a high pressure, steel, insulated pipeline and the heat loss involved, normally the distance between the landfill and steam purchaser is limited to 1.6 km (1 mile), and preferably less. Ratio of gas used to generate steam to gas recovered will range from 0.92 to 0.96 and boiler conversion efficiency should be in the range of 75 to 85 percent. Because the boiler is located

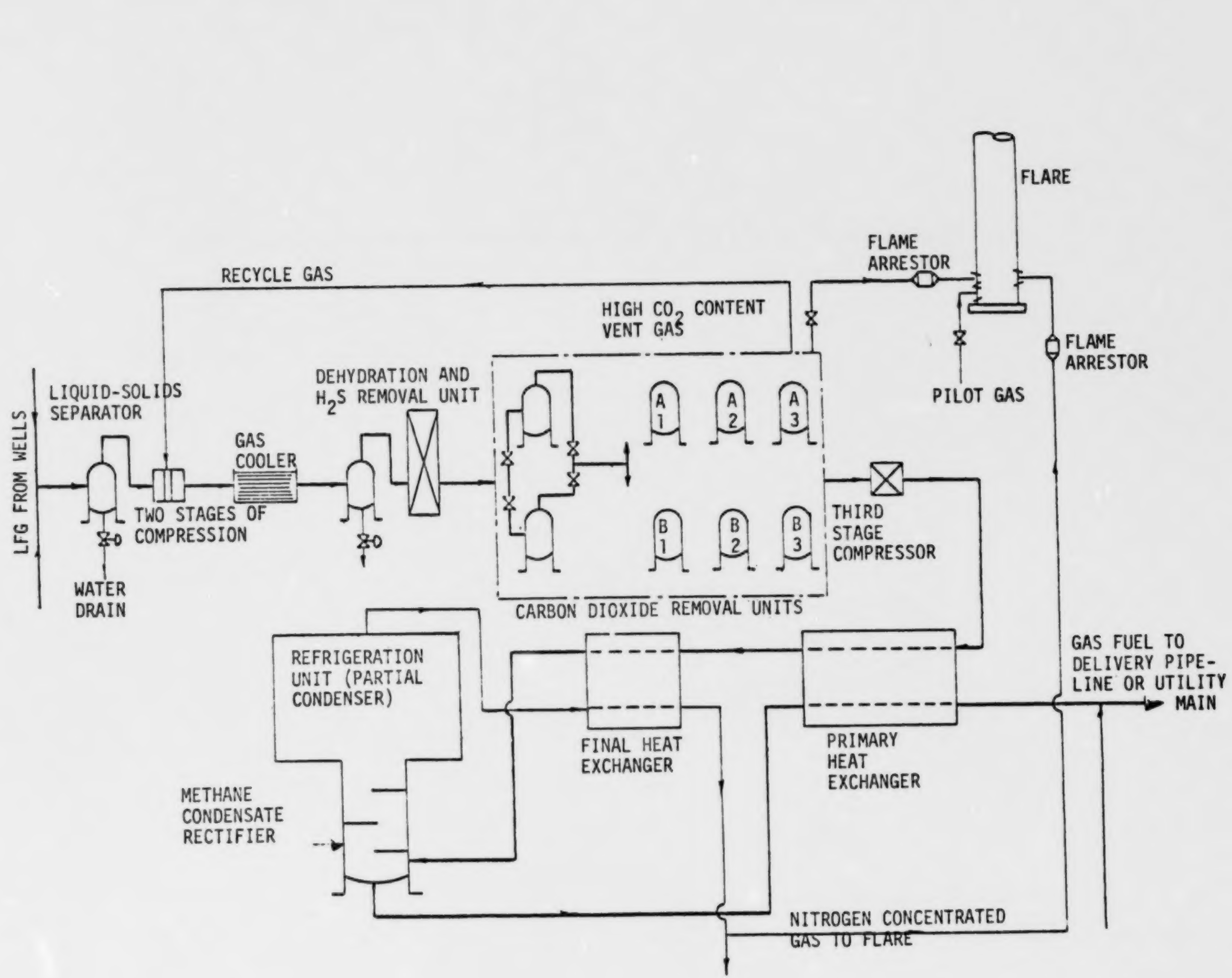

RECYCLE GAS
HIGH CO$_2$ CONTENT VENT GAS
FLAME ARRESTOR
FLARE
FLAME ARRESTOR
PILOT GAS
LFG FROM WELLS
LIQUID-SOLIDS SEPARATOR
WATER DRAIN
TWO STAGES OF COMPRESSION
GAS COOLER
DEHYDRATION AND H$_2$S REMOVAL UNIT
A 1
A 2
A 3
B 1
B 2
B 3
CARBON DIOXIDE REMOVAL UNITS
THIRD STAGE COMPRESSOR
REFRIGERATION UNIT (PARTIAL CONDENSER)
METHANE CONDENSATE RECTIFIER
FINAL HEAT EXCHANGER
PRIMARY HEAT EXCHANGER
GAS FUEL TO DELIVERY PIPE-LINE OR UTILITY MAIN
NITROGEN CONCENTRATED GAS TO FLARE

Figure 6. Alternative III - Upgrading to 36387 kJ/std cu m fuel gas.

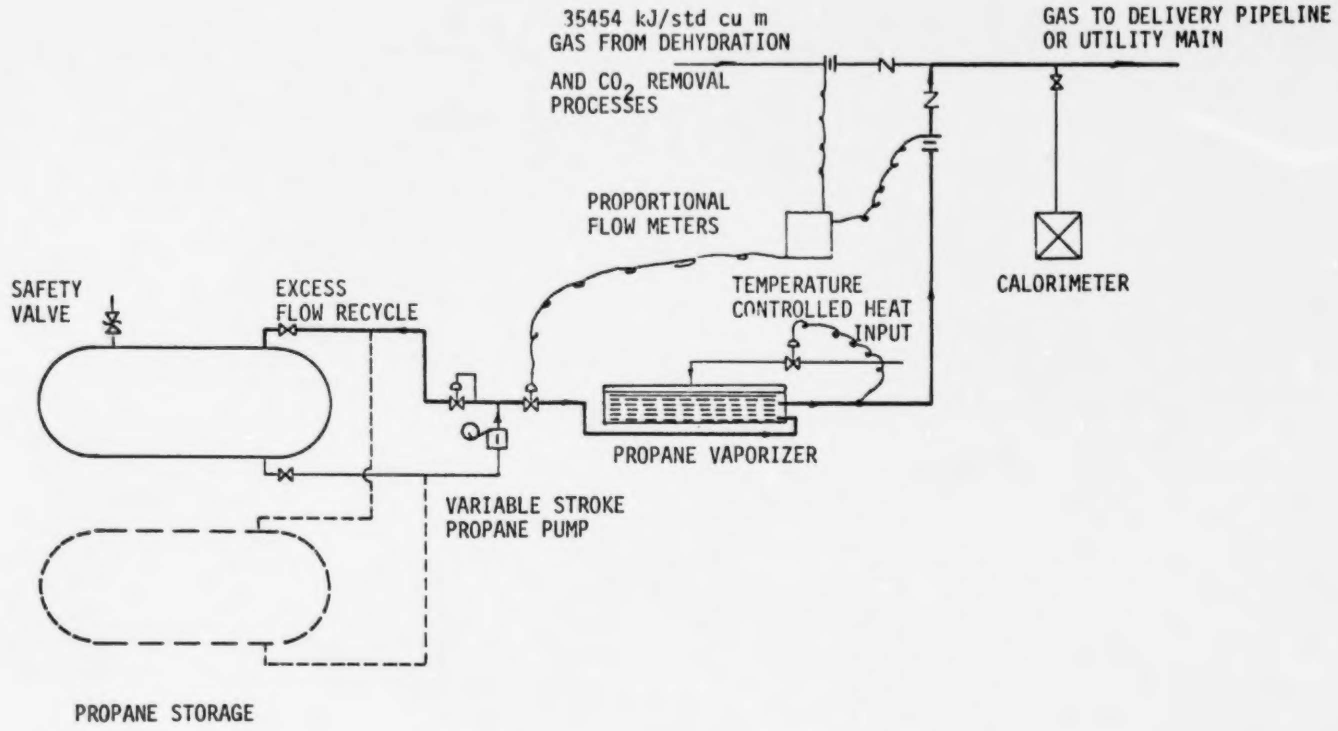

35454 kJ/std cu m
GAS FROM DEHYDRATION
AND CO_2 REMOVAL
PROCESSES
GAS TO DELIVERY PIPELINE
OR UTILITY MAIN
PROPORTIONAL
FLOW METERS
CALORIMETER
SAFETY
VALVE
EXCESS
FLOW RECYCLE
TEMPERATURE
CONTROLLED HEAT
INPUT
PROPANE VAPORIZER
VARIABLE STROKE
PROPANE PUMP
PROPANE STORAGE

Figure 7. Alternative IV - Upgrading and propane blending to 37320 kJ/std cu m gas.

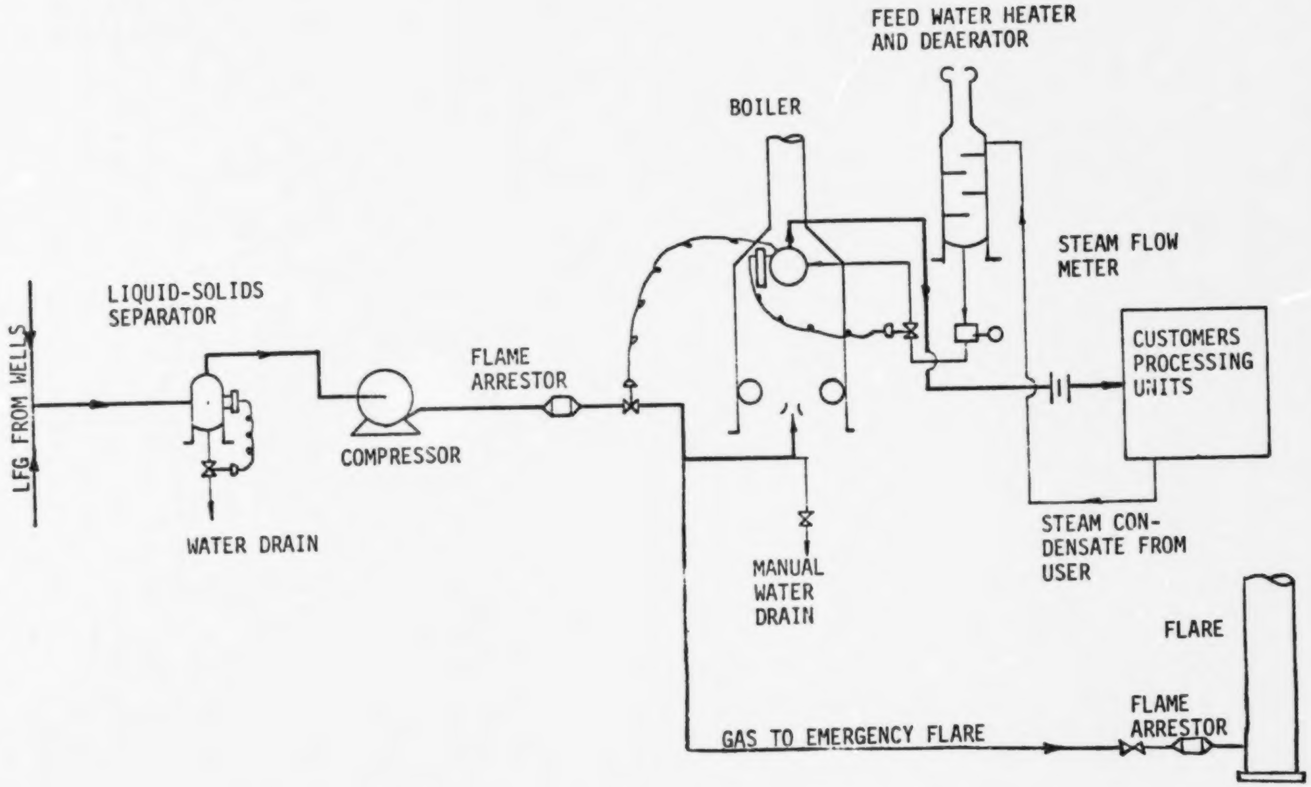

LFG FROM WELLS
LIQUID-SOLIDS SEPARATOR
WATER DRAIN
COMPRESSOR
FLAME ARRESTOR
BOILER
FEED WATER HEATER AND DEAERATOR
STEAM FLOW METER
CUSTOMERS PROCESSING UNITS
STEAM CON- DENSATE FROM USER
MANUAL WATER DRAIN
FLARE
FLAME ARRESTOR
GAS TO EMERGENCY FLARE

Figure 8. Alternative V - Low or medium pressure/temperature steam generation.

on-site, dehydration is unnecessary although provisions must be made in the on-site landfill gas pipeline to drain water and the pipeline must be corrosion resistant (constructed of plastic material such as PVC).

Alternative VI - Electricity Generation, Steam Turbine

Shown in Figure 9, this alternative uses the same system as Alternative V to generate medium pressure/temperature steam that is then supplied to a steam turbine-generator to generate electricity. As in Alternative V, the only processing applied to the raw landfill gas is to separate condensed water and any entrapped particulates followed by low pressure, 34 to 69 kN/sq m (5 to 10 psig) compression to deliver the gas to the boiler burners. Electricity is transformed to appropriate voltage for transmission to one or more ultimate users or to the local utility after the current has been synchronized with the power supply.

Alternative VII - Electricity Generation, Gas Turbine

For this alternative, raw landfill gas from which the condensate and particulates have been removed, is compressed in a three stage compressor to about 1379 kN/sq m (200 psig). It is cooled and additional condensate removed before being fed to one or more gas turbine-generator sets. This alternative is based on presently available industrial gas turbines or those expected to be available in one or two years. As can be observed from the schematic in Figure 10, this electricity generation system is somewhat simpler than that required for a steam turbine since it avoids the intermediate transformation to steam. Ratio of landfill gas delivered to the gas turbine to energy recovered will range from about 0.82 to 0.87 primarily due to the gas consumed by the gas engine driven compressors. If the gas turbines are used to drive the compressors through a suitable gear box, capital costs may be reduced somewhat but an equivalent amount of turbine shaft horsepower will be used. The net power available for delivery will thus be about the same as for the system employing gas engine driven compressors.

Alternative VIII - Electricity Generation, Gas Engine

This alternative is similar to Alternative VII although somewhat simpler in requiring only low pressure compression, 34 to 69 kN/sq m (5 to 10 psig) for delivery to the gas engine prime mover. Raw landfill gas is passed through a liquid-solids separator enroute to the compressor that delivers the gas to the gas engine, a heavy duty, low speed, spark ignition type otto cycle engine. For this analysis, single and multiple 2.34 MM kJ (650 kw) gas engine-generator sets were used, although lower capacity sets are available. Ratio of gas delivered to the engine to that recovered will be in the 0.92 to 0.96 range. Equipment costs for gas engine driven generator sets are less than for steam turbine or gas turbine sets, but maintenance on the reciprocating engine can be expected to be considerably greater than for the purely rotational turbines. Figure 11 demonstrates the relative simplicity of this alternative.

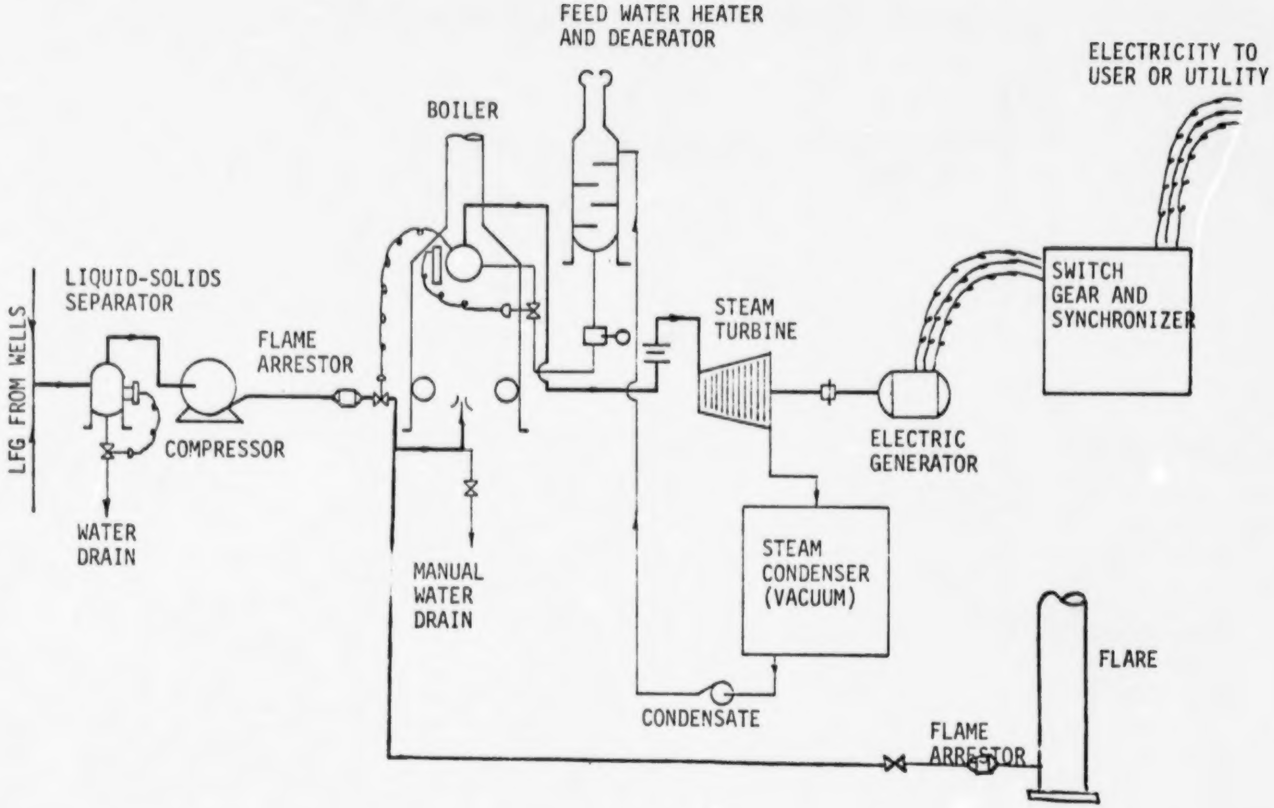

LFG FROM WELLS
LIQUID-SOLIDS SEPARATOR
WATER DRAIN
COMPRESSOR
FLAME ARRESTOR
BOILER
MANUAL WATER DRAIN
FEED WATER HEATER AND DEAERATOR
STEAM TURBINE
CONDENSATE
STEAM CONDENSER (VACUUM)
ELECTRIC GENERATOR
SWITCH GEAR AND SYNCHRONIZER
ELECTRICITY TO USER OR UTILITY
FLAME ARRESTOR
FLARE

Figure 9. Alternative IV - Electricity generation (steam turbine).

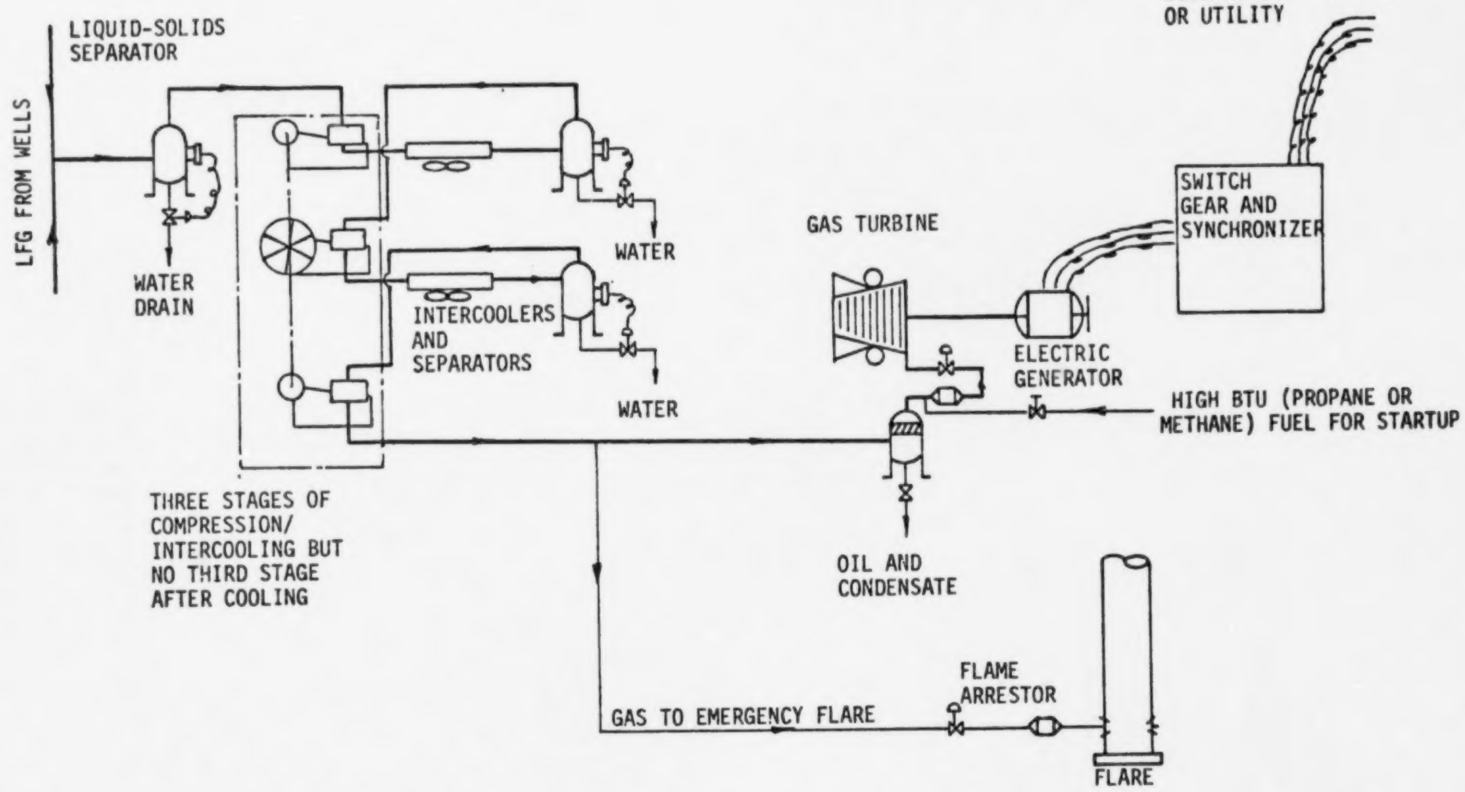

ELECTRICITY TO USER OR UTILITY
LIQUID-SOLIDS SEPARATOR
LFG FROM WELLS
WATER DRAIN
WATER
WATER
INTERCOOLERS AND SEPARATORS
SWITCH GEAR AND SYNCHRONIZER
GAS TURBINE
ELECTRIC GENERATOR
HIGH BTU (PROPANE OR METHANE) FUEL FOR STARTUP
THREE STAGES OF COMPRESSION/ INTERCOOLING BUT NO THIRD STAGE AFTER COOLING
OIL AND CONDENSATE
GAS TO EMERGENCY FLARE
FLAME ARRESTOR
FLARE

Figure 10. Alternative VII - Electricity generation (gas turbine).

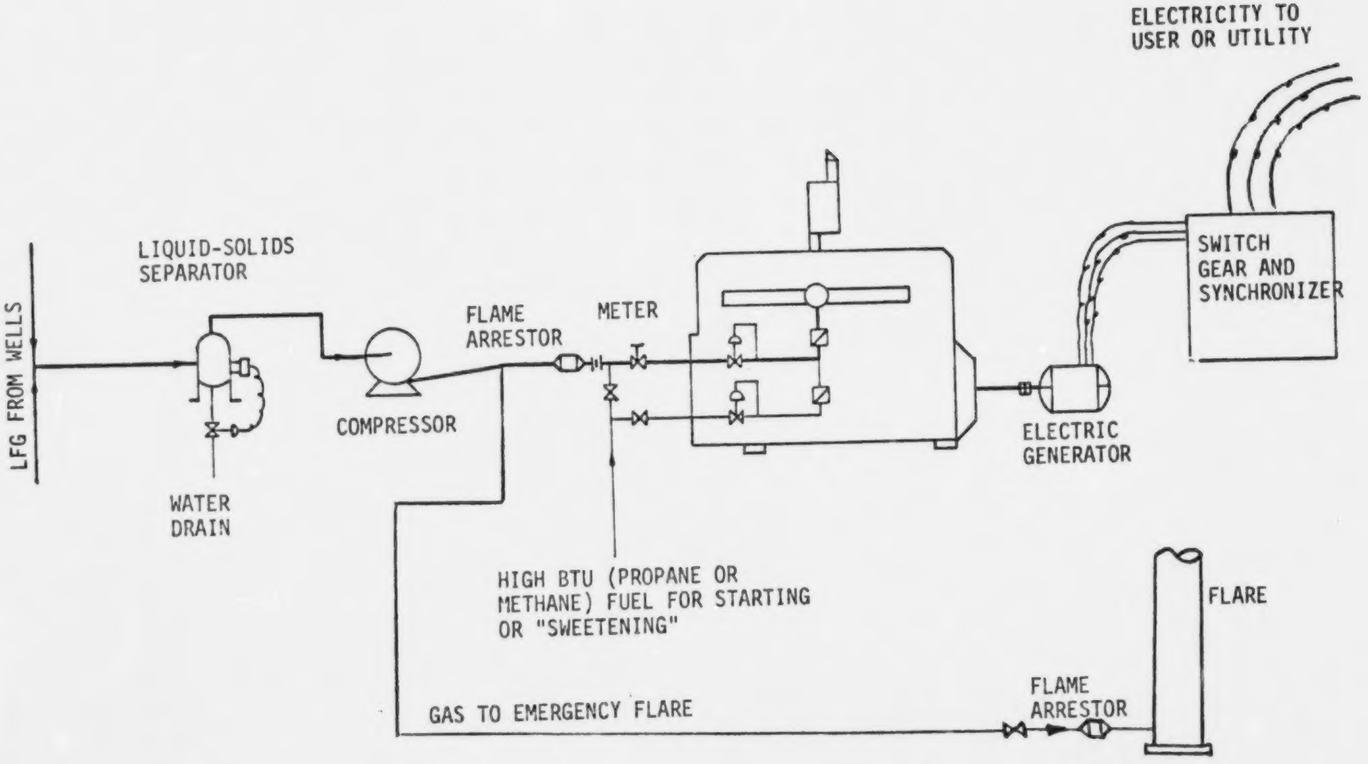

ELECTRICITY TO
USER OR UTILITY
LFG FROM WELLS
LIQUID-SOLIDS
SEPARATOR
WATER
DRAIN
COMPRESSOR
FLAME
ARRESTOR
METER
SWITCH
GEAR AND
SYNCHRONIZER
ELECTRIC
GENERATOR
HIGH BTU (PROPANE OR
METHANE) FUEL FOR STARTING
OR "SWEETENING"
FLARE
GAS TO EMERGENCY FLARE
FLAME
ARRESTOR

Figure 11. Alternative VIII - Electricity generation (gas engine).

Alternative IX - Methanol Synthesis

Noted earlier, methanol synthesis was selected as representative of use of upgraded landfill gas as a feed stock for conversion to another compound; it is probably the most cost-effective of three possibilities; methanol, ammonia and urea. Figure 12 shows in simplified form the basic schematic for this alternative. To convert high methane content gas to methanol requires the addition of high pressure compression, reforming and catalytic conversion following the dehydration and carbon dioxide removal steps of Alternative II. Because of the high pressure and gas purity required for the conversion (to avoid poisoning the catalyst), conversion to methanol tends to be an expensive process and one that results in about a 67 percent loss of available energy. It is presented to demonstrate the basic economics of using upgraded landfill gas as a chemical feed stock.

COST AND ECONOMICS OF ALTERNATIVE LANDFILL GAS UITLIZATIONS

In order to develop economic comparisons of alternative landfill gas uses, showing the economic relationships for various gas recovery quantities and processes for each product, the following standardized product values were used.

Product	Purchaser	Value
Dehydrated LFG	Industrial or institutional	Retail natural gas (N.G.) price $2.00/1.05 MM kJ (MM BTUs)
Steam	Industrial or institutional	Gas used to generate steam - $2.00/1.05 MM kJ (MM BTUs)
Electricity	Industrial or institutional	Retail price $0.05/kw-hr
Electricity	Utility	Wholesale price $0.03/kw-hr
Upgraded LFG	Utility	Wholesale N.G. price $1.65/1.05 MM kJ
Methanol	Industrial	$0.092/L ($0.35/gal)

For cost estimating purposes, standardized investment capital loan interest rates were used as follows:

LFG Recovery Subsystem	10 year amortization at 8.5 percent annual interest
Process Subsystem	20 year amortization at 8.5 percent annual interest

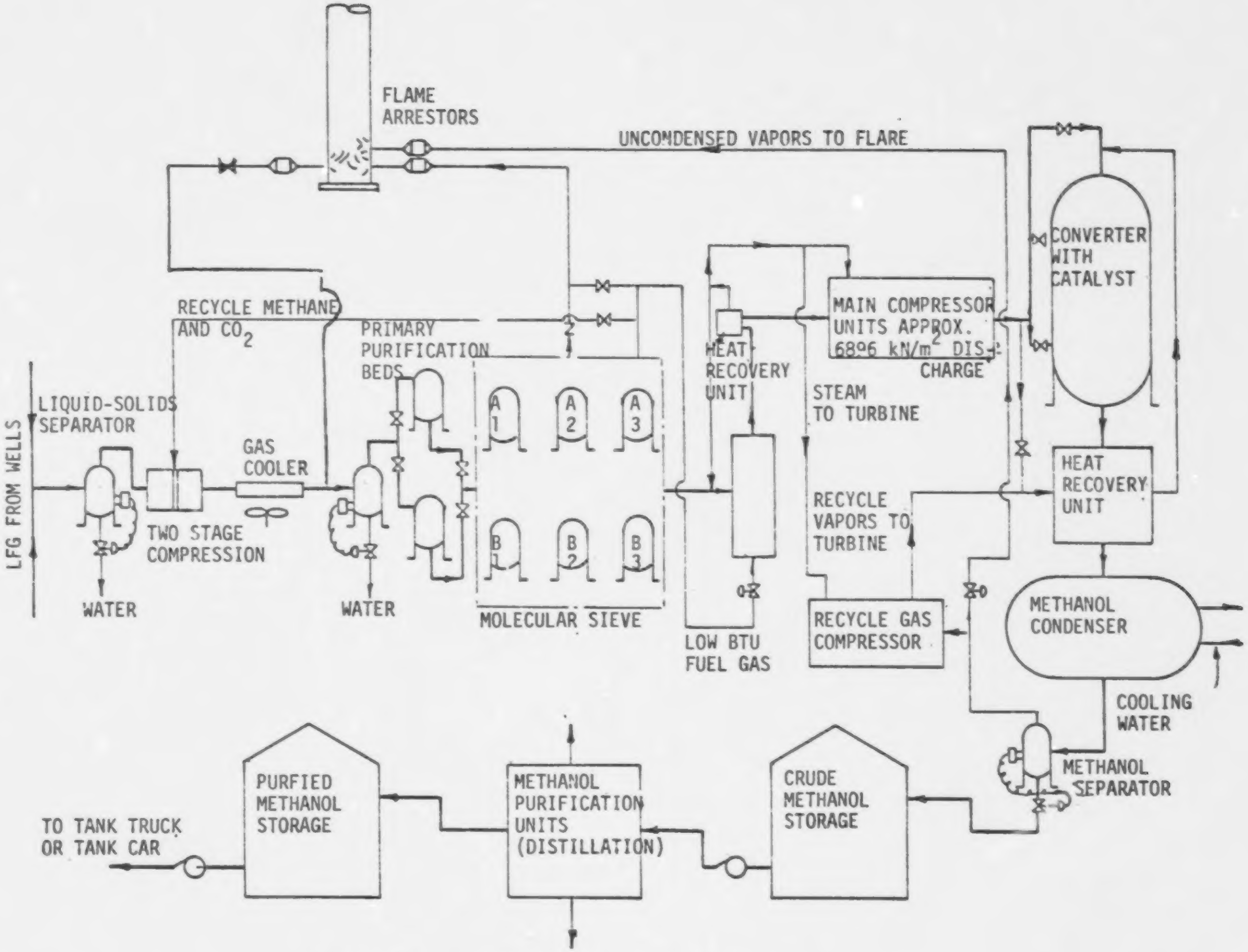

FLAME ARRESTORS
UNCONDENSED VAPORS TO FLARE
CONVERTER WITH CATALYST
RECYCLE METHANE AND CO_2
PRIMARY PURIFICATION BEDS
MAIN COMPRESSOR UNITS APPROX. 6896 kN/m^2 DISCHARGE
HEAT RECOVERY UNIT
STEAM TO TURBINE
LIQUID-SOLIDS SEPARATOR
LFG FROM WELLS
GAS COOLER
A 1
A 2
A 3
B 1
B 2
B 3
HEAT RECOVERY UNIT
TWO STAGE COMPRESSION
RECYCLE VAPORS TO TURBINE
WATER
WATER
MOLECULAR SIEVE
LOW BTU FUEL GAS
RECYCLE GAS COMPRESSOR
METHANOL CONDENSER
COOLING WATER
METHANOL SEPARATOR
PURFIED METHANOL STORAGE
METHANOL PURIFICATION UNITS (DISTILLATION)
CRUDE METHANOL STORAGE
TO TANK TRUCK OR TANK CAR

Figure 12. Alternative IX - Methanol synthesis.

Delivery Pipeline	10 year amortization at 8.5 percent annual interest

A shorter amortization period was used for the recovery and delivery subsystems because of the uncertainties in the period in which a mature landfill can be expected to produce gas at a rate sufficient to warrant recovery, processing and sale. However, major process equipment normally has a useful life of at least 20 years, and frequently more with proper maintenance, overhaul and parts replacement. The assumption is that after about ten or more years the landfill gas generation rate may be reduced to the point that recovery becomes uneconomical, thus the recovery system and pipeline cost must be amortized over that period. In contrast, however, the process system could be moved to another site and used for at least an additional ten years or sold at about one-half replacement value to another operator.

The number of system operating days per year are based on the type of system and equipment involved. Even though the demand characteristics of most industrial users are from 8 to 24 hours per day, and from five to seven days per week, such that there could be significant number of non-delivery hours or days per month, gas delivery rates can be increased over the average recovery rate based on a continuous operating cycle using the landfill as the short term storage vessel. Stoppages during normal delivery periods are allowed for in the number of annual days of plant operation estimated to be between 330 to 350 days per year for all but methanol synthesis which is assigned 300 days per year.

Material, equipment and construction cost estimates are based on late 1977 and early 1978 prices and all economic analysis was conducted in current, 1978 dollars. Because of broad variations in local conditions, costs of land, construction loan interest and working capital are not included in the economic analysis. Also, since the ratio of equity to loan capital varies widely, the assumption is that return on equity capital will be equal to the equity to loan capital ratio. Because of similar broad variations, income taxes and local property taxes are not included. Thus profit and return on investment are computed before all applicable taxes are deducted. Representative gross returns on investment (ROI) are used to estimate daily landfill gas (LFG) recovery quantities necessary for system economic viability.

Operating costs include interest and amortization for each of the three subsystems: recovery, processing and delivery, based on a standard 8.5 percent interest rate, with amortization periods of ten years for recovery and delivery subsystems and 20 years for process subsystems as noted above; and salary and wage costs (fringe benefits, employment taxes, etc.) for all employees. Also included are costs of replacement parts and other consumables, utilities and other direct costs. This last category covers highly specialized maintenance and service labor and materials that are required too infrequently to support full-time specialized personnel, and therefore, are purchased from special firms or factory representatives providing these services.

The cost of completing a landfill or developing a new landfill as part of the landfill gas recovery/process/utilization system was not included as a cost element. Revenues collected at the landfill gate or transfer station to cover cost of landfill disposal similarly were not included. The cost of the landfill was treated as a "sunk" cost for completed landfills, and a non-accountable cost for new landfills since the general practice in the United States is to set unit drop charges equal to unit landfill disposal costs. Because landfilling costs and corresponding drop charges vary widely among the different regions of the nation, this treatment avoids the necessity of accounting for this highly variable cost-revenue element.

As a consequence of the assumptions made above and the inability to accommodate certain cost items because of large regional variances, users of these economic analyses should make appropriate adjustments to suit local conditions and financial factors. The cost estimates and economic analysis results are arranged so that major capital and operating costs and interest and amortization are identified and can be readily adjusted when evaluating the feasibility of a site specific project.

Alternative Recovery/Process/Utilization System Cost Estimates

An assumption made for purposes of maintaining consistency between cost estimates is that each system operates continuously with constant or equivalent fluctuations in demand for the specified number of days per year. Each capital cost estimate is divided into three subsystems:

1. Recovery subsystem

2. Process subsystem

3. Delivery subsystem

Costs of landfill gas recovery systems consisting of a number of wells, a collection pipeline system and appropriate ancillaries were taken from Figure 13, based on experience with a number of landfill gas projects. As representative costs, the deep landfill, 30.5 to 45.7 m (100 to 150 ft) curve was used. Shallow landfill gas mining costs are approximately twice the cost of a deep landfill as shown on the curve because about twice the number of wells are required for the same quantity of solid waste emplaced. For purposes of standardization, the curves are based on a gas flow of 8.7 std cu m (600 scfm) per million metric tons (tons) of emplaced waste.

Figure 14 shows the relationships of normalized delivery subsystems with product flow rates for the three types of products produced by the alternative process systems: gas, steam and electricity. These curves were developed from current A/E cost estimates assuming underground lines, average soils and construction conditions. Cost of the delivery subsystem is included in each alternative using average pipeline or transmission line lengths: 5 km (3 mi) for gas and electric transmission lines, and 1.6 km (1 mi) for steam lines.

A summary follows for each alternative, listing estimated capital and

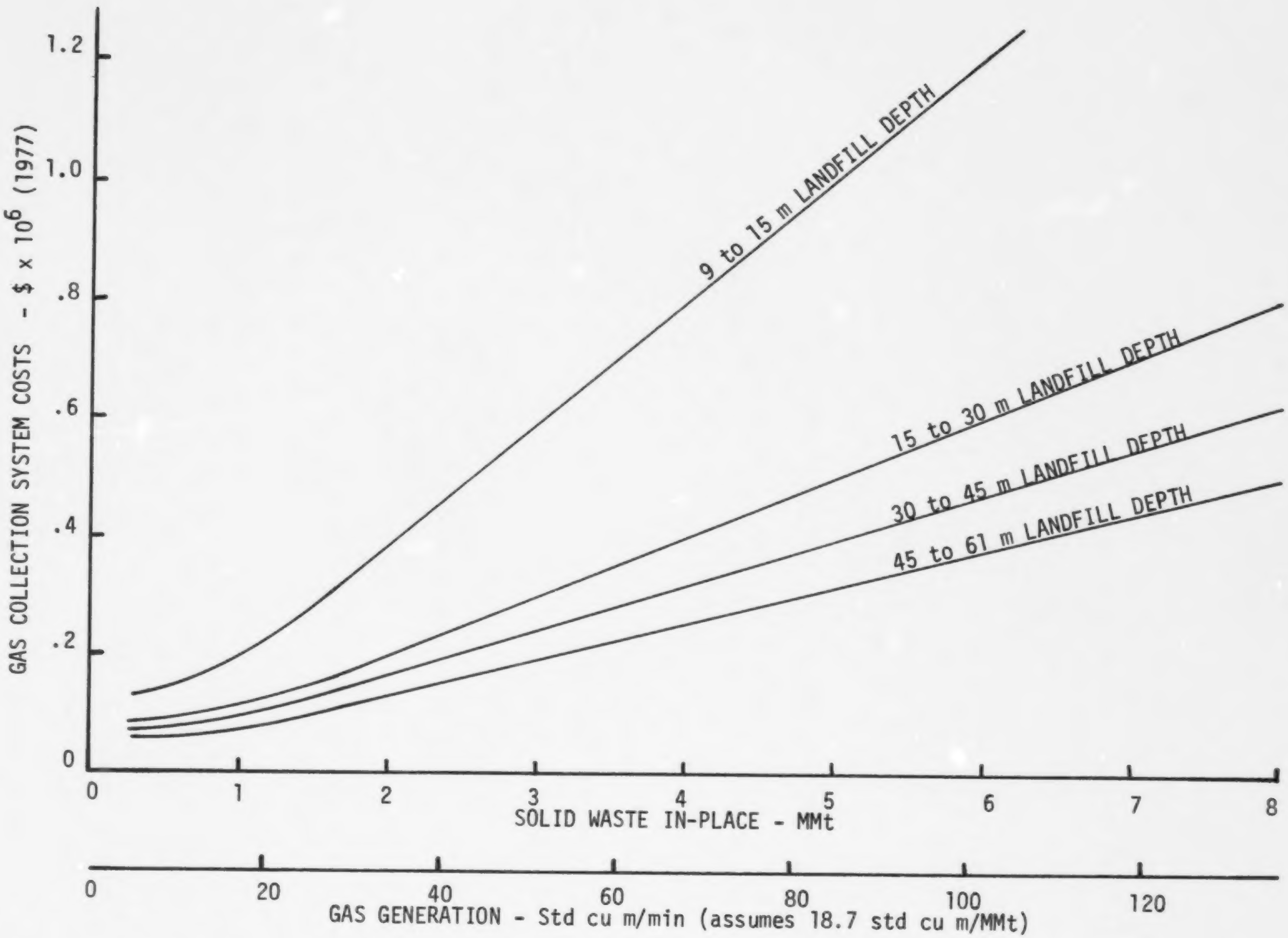


Figure 13. Capital costs of landfill gas recovery subsystem.

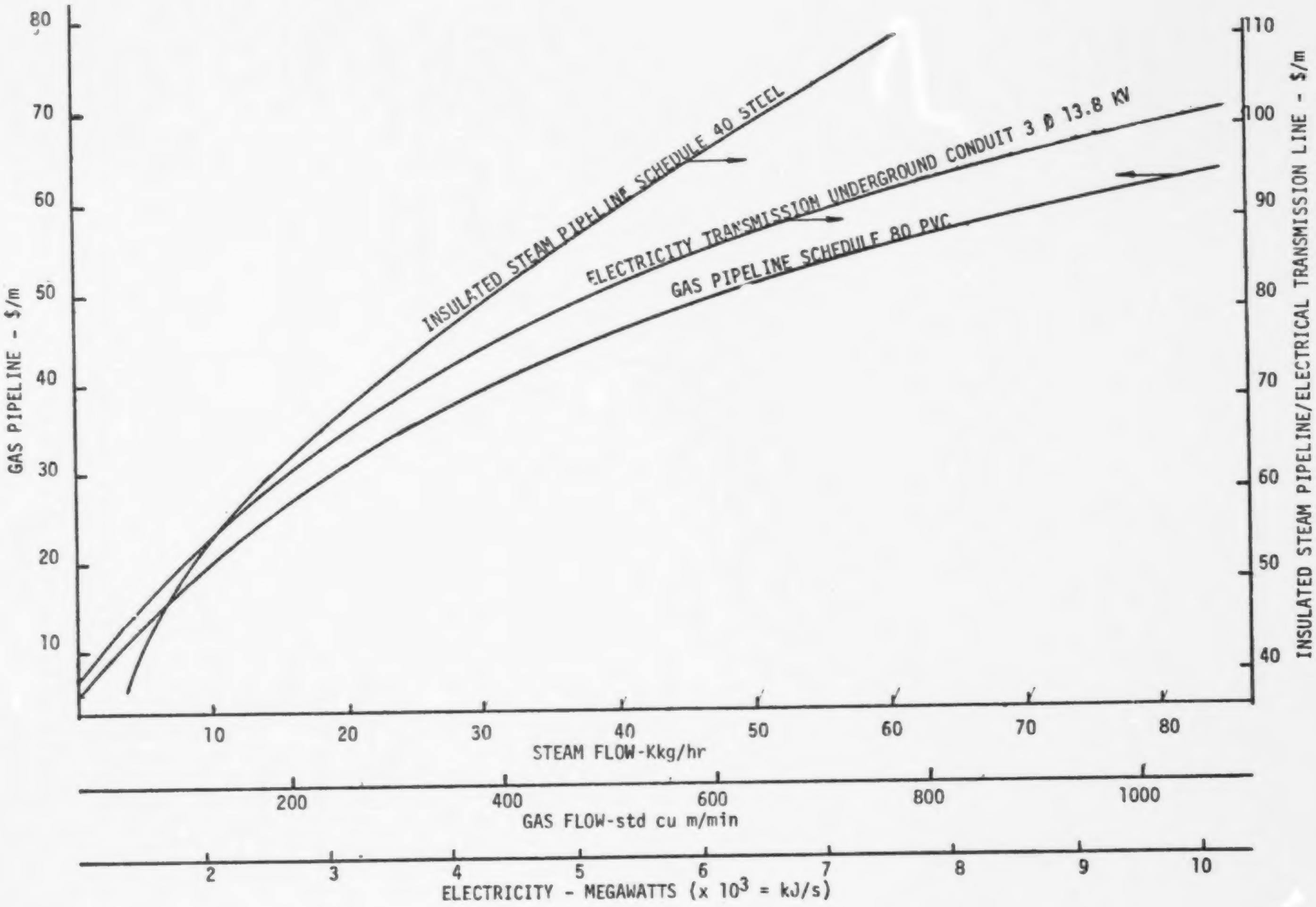


Figure 14. Power transmission line and insulated steam and gas pipeline costs.

annual operating costs for different LFG recovery rates and size of landfills.

Landfill Gas Processing Alternatives

Tables 8 through 11 list capital and annual operating cost data for each of the four gas upgrade processes considered in this study: dehydration and compression; dehydration and carbon dioxide removal; dehydration, carbon dioxide and nitrogen removal; and dehydration, carbon dioxide removal and propane blending to provide landfill gas products with heating values of 17727, 35454, 36387, and 37320 kJ/std cu m (475, 950, 975, and 1000 BTU/scf), respectively. Figure 15 shows the variation of unit costs with daily landfill gas recovery rates for these four processes compared against retail and wholesale natural gas unit prices. The curves are as expected for the four types of processing. As was expected, blending about 1 percent of propane with landfill gas from which both water vapor and carbon dioxide have been removed significantly reduces the cost of producing an upgraded LFG with a heating value equivalent to that of natural gas.

The cost curves indicate that for local government ownership and operation of landfills, where there are no requirements for revenues to cover taxes and return on investment, and when the gas can be sold for $2.00/37.32 MM kJ (MM BTUs) heating value; the systems described are economically viable for landfills with low-flow rates. For dehydration only, a flow rate of 7.8 std cu m/min (0.4 MM scf/day, 275 scfm) may be viable. For dehydration and carbon dioxide removal, 29.7 std cu m/min (1.5 MM scf/day, 1050 scfm) may be viable. For dehydration, carbon dioxide removal and propane blending, 48.8 std cu m/min (2.2 MM scf/day, 1525 scfm) may be viable. Finally, 94.8 std cu m/min (4.8 MM scf/day, 3350 scfm) may be viable for dehydration and removal of both carbon dioxide and nitrogen. To relate gas flows to landfill size, a typical landfill with about 4.54 MM t (5 MM T) emplaced can be expected to produce between 56.6 to 70.8 std cu m/min (2000 and 2500 scfm) of LFG. Such a landfill typically would have a fill volume of about 9.94 MM cu m (13 MM cu yd) assuming 20 percent cover material. Thus, a large landfill would be the only facility likely to produce enough gas to render dehydration, carbon dioxide and nitrogen removal a break-even operation even for local government.

The situation for private ownership and operation is much different from that of local government and is discussed in the subsection on alternative economics.

Landfill Gas Conversion Alternatives

Tables 12 through 15 list capital and annual operating cost estimates for alternative methods of converting LFG to other energy forms-steam or electricity, and Table 16 list data for methanol synthesis from LFG. To fully explore costs of electricity generation, three different prime movers were used as described in the introduction of this section. Figure 16 depicts the relationships of unit costs for these conversion processes with variations in landfill gas recovery rates.

TABLE 8. COST ESTIMATE SUMMARY - ALTERNATE I

LFG Dehydration and Compression

Input (cu m/min)	13.74	34.69	69.38	137.35
Output[a] (std cu m/min)	13.03	32.85	65.70	130.13
Capital Costs (M$)				
Recovery Subsystem[b]	80	159	309	630
Process Subsystem				
Equipment	300	428	590	1,044
Facilities	47	55	70	100
Design	30	40	55	85
Construction	80	100	115	130
Total	457	623	830	1,359
Delivery Subsystem[c]	99	175	249	330
Total System	636	957	1,388	2,319
Annual Operating Costs (M$)				
Amortization & Interest Recovery Subsystem	12.2	24.2	47.1	96.0
Process Subsystem	48.3	65.8	87.7	143.6
Delivery Subsystem	15.1	26.7	38.0	50.3
Total A&I	75.6	116.7	172.8	289.9
Salaries & Wages & S/W Costs	70.0	76.3	80.0	86.0
Consumables & Parts	8.0	15.0	25.0	45.0
Utilities	21.0	50.0	92.0	180.0
Other[d]	10.0	15.0	17.5	28.8
Total	109.0	156.3	214.5	339.8
Total Annual Op. Cost	184.6	273.0	387.3	629.7
Daily Energy Output (MM kJ)	331.9	830.1	1660.2	3320.3
No. Annual Days Operation	350	350	350	350
Annual Energy Output (10^9 kJ)	116.2	290.6	581.1	1162.1
Cost ($/MM kJ)	1.589	0.939	0.667	0.542

[a] Dehydrated LFG at 17727 kJ/std cu m (475 BTU/scf) and 155 kN/sq m (22.5 psig).
[b] 30.5 to 45.7 m (100 to 150 ft) average fill depth - Figure 13.
[c] 5 km (3 mi) long - Figure 14.
[d] Purchased services and maintenance.

TABLE 9. COST ESTIMATE SUMMARY - ALTERNATE II

LFG Dehydration and Carbon Dioxide Removal

Input (cu m/min)	47.29	94.45	141.60
Output (std cu m/min)[a]	13.74	27.47	42.34
Capital Costs (M$)			
Recovery Subsystem[b]	215	430	645
Process Subsystem			
Equipment	1,130	1,740	2,355
Facilities	70	95	125
Design	90	140	185
Construction	135	210	280
Total	1,425	2,185	2,945
Delivery Subsystem[c]	100	157	202
Total System	1,740	2,772	3,792
Annual Operating Costs (M$)			
Amortization & Interest Recovery Subsystem	32.8	65.5	98.3
Process Subsystem	150.6	230.9	311.2
Delivery Subsystem	15.2	23.9	30.8
Total A&I	198.2	320.4	440.3
Salaries & Wages & S/W Costs	96.0	99.0	102.2
Consumables & Parts	20.0	35.0	50.0
Utilities	20.0	38.0	55.0
Other[d]	25.0	45.0	55.0
Total	161.0	217.0	262.2
Total Annual Op. Cost	359.2	537.4	702.5
Daily Energy Output (MM kJ)	700.9	1401.8	2153.3
No. Annual Days Operation	330	330	330
Annual Energy Output (10^9 kJ)	231.4	462.6	710.6
Cost ($/MM kJ)	1.552	1.161	0.989

[a] Upgraded LFG at 35454 kJ/std cu m (950 BTU/scf and 1379 kN/sq m (200 psig).
[b] 30.5 to 45.7 m (100 to 150 ft) average fill depth in Figure 13.
[c] 5 km (3 mi) long - Figure 14.
[d] Purchased services and maintenance.

TABLE 10. COST ESTIMATE SUMMARY - ALTERNATE III

LFG Dehydration and Carbon Dioxide and Nitrogen Removal

Input (cu m/min)	47.29	94.45	141.60
Output[a] (std cu m/min)	11.89	24.64	40.36
Capital Costs (M$)			
Recovery Subsystem[b]	215	430	645
Process Subsystem			
Equipment	1,830	2,770	3,675
Facilities	120	165	235
Design	135	190	255
Construction	220	335	445
Total	2,305	3,460	4,610
Delivery Subsystem[c]	92	148	195
Total System	2,612	4,038	5,450
Annual Operating Costs (M$)			
Amortization & Interest Recovery Subsystem	32.8	65.5	98.3
Process Subsystem	243.6	365.7	487.2
Delivery Subsystem	14.0	22.6	29.7
Total A&I	290.4	453.8	615.2
Salaries & Wages & S/W Costs	150.0	153.0	156.2
Consumables & Parts	35.0	60.0	85.0
Utilities	40.0	75.0	115.0
Other[d]	40.0	65.0	80.0
Total	265.0	353.0	436.2
Total Annual Op. Cost	555.4	806.8	1,051.4
Daily Energy Output (MM kJ)	616.6	1,284.5	2,106.7
No. Annual Days Operation	330	330	330
Annual Energy Output (10^9 kJ)	203.5	423.9	695.2
Cost ($/MM kJ)	2.729	1.903	1.512

a Upgraded LFG at 36387 kJ/std cu m (975 BTU/scf) and 1379 kN/sq m (200 psig).
b 30.5 to 45.7 m (100 to 150 ft) average fill depth - Figure 13.
c 5 km (3 mi) long - Figure 14.
d Purchased services and maintenance.

TABLE 11. COST ESTIMATE SUMMARY - ALTERNATE IV

LFG Dehydration, Carbon Dioxide Removal and Propane Blending

Input (cu m/min)	47.29	94.45	141.60
Output[a] (std cu m/min)	14.22	28.43	43.70
Capital Costs (M$)			
Recovery Subsystem[b]	215	430	645
Process Subsystem			
Equipment	1,170	1.785	2,405
Facilities	80	110	145
Design	94	145	190
Construction	140	217	288
Total	1,484	2,257	3,028
Delivery Subsystem[c]	103	160	204
Total System	1,802	2,847	3,877
Annual Operating Costs (M$)			
Amortization & Interest Recovery Subsystem	32.8	65.5	98.3
Process Subsystem	156.8	238.5	320.0
Delivery Subsystem	15.7	24.4	31.1
Total A&I	205.3	328.4	449.4
Salaries & Wages & S/W Costs	96.0	99.0	102.2
Consumables & Parts[d]	110.0	210.0	321.0
Utilities	22.0	41.0	59.0
Other[e]	30.0	52.0	60.0
Total	258.0	402.0	542.2
Total Annual Op. Cost	463.3	730.4	991.6
Daily Energy Output (MM kJ)	762.1	1,524.3	2,342.0
No. Annual Days Operation	330	330	330
Annual Energy Output (10^9 kJ)	251.5	503.1	772.9
Cost ($ /MM kJ)	1.843	1.452	1.283

a Upgraded LFG at 37320 kJ/std cu m (1,000 BTU/scf) and 1379 kN/sq m (200 psig).
b 30.5 to 45.7 m (100 to 150 ft) average depth - Figure 13.
c 5 km (3 mi) long - Figure 14.
d Includes propane at $0.106/L ($0.40/gal), HHV = 93300 kJ/std cu m.
e Purchased services and maintenance.

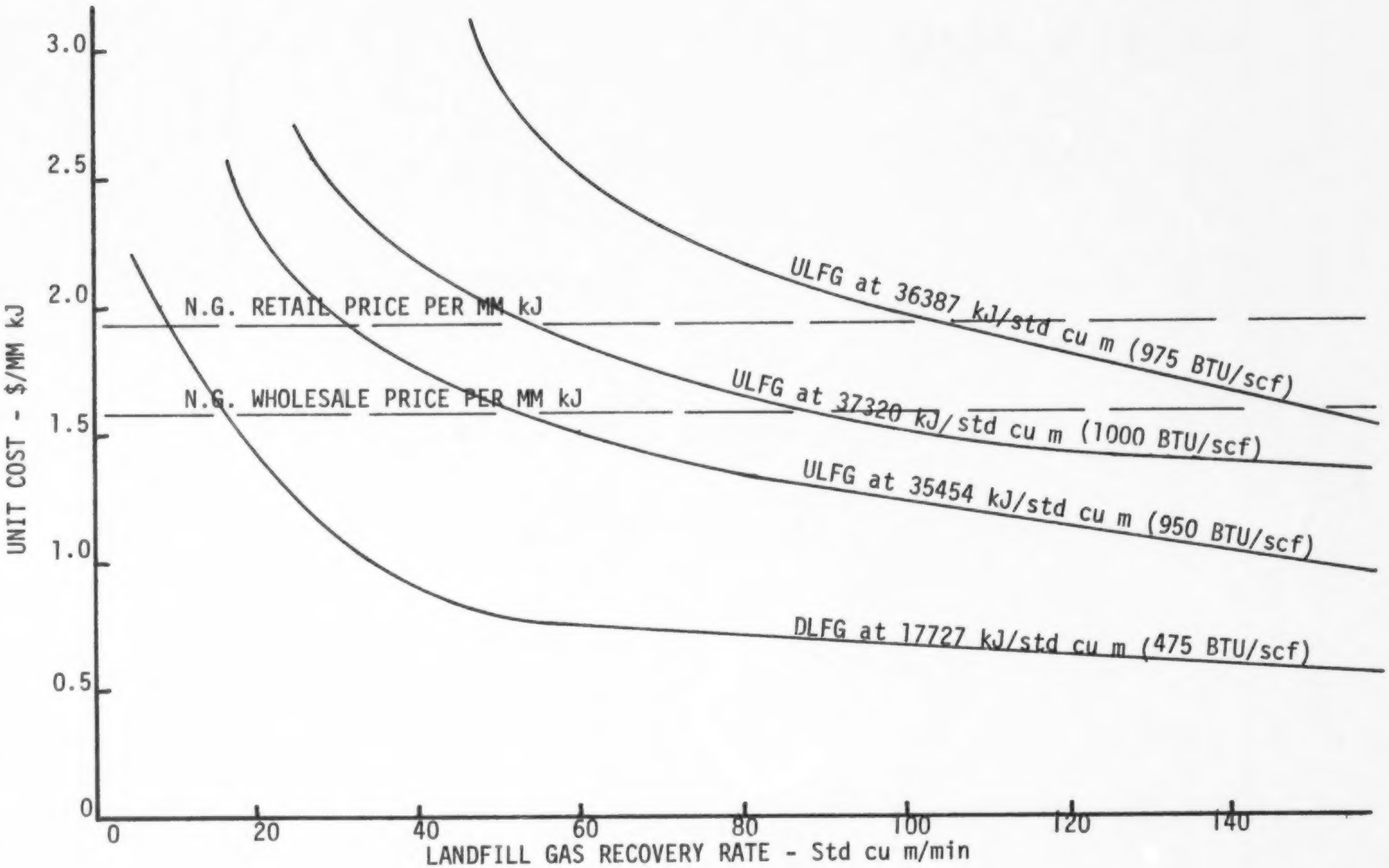


Figure 15. Unit cost of alternative landfill gas products

TABLE 12. COST ESTIMATE SUMMARY - ALTERNATE V

LFG Medium Pressure/Temperature Steam Generation

Input (cu m/min)	10.20	25.20	50.41	100.68	150.80
Output (kg/hr steam[a])	3,632	9,080	18,160	36,320	54,480
Capital Costs (M$)					
Recovery Subsystem[b]	66	120	228	460	700
Process Subsystem					
Equipment	180	345	560	1,100	1,650
Facilities	14	30	50	85	115
Design	19	35	58	98	111
Construction	30	58	95	198	330
Total	243	468	763	1,481	2,206
Delivery Subsystem[c]	63	85	106	137	163
Total System	372	673	1,097	2,078	3,069
Annual Operating Costs (M$)					
Amortization & Interest Recovery Subsystem	10.1	18.3	34.7	70.1	106.7
Process Subsystem	25.7	49.5	80.6	156.5	233.2
Delivery Subsystem	9.6	13.0	16.2	20.9	24.8
Total A&I	45.4	80.8	131.5	247.5	364.7
Salaries & Wages & S/W Costs	66.6	70.1	72.3	80.5	90.0
Consumables & Parts	5.0	8.0	12.0	20.0	27.0
Utilities	6.1	13.0	20.0	37.0	52.0
Other[d]	5.0	5.0	10.0	17.5	20.0
Total	82.7	96.1	114.3	150.3	189.0
Total Annual Op. Cost	128.1	176.9	245.8	402.5	553.7
Daily Energy Output (MM kJ)[e]	208.6	521.6	1,043.2	2,086.4	3,129.6
No. Annual Days Operation	350	350	350	350	350
Annual Energy Output (10^9 kJ)	73.0	182.6	365.1	730.2	1,095.3
Cost ($/MM kJ)	1.753	0.969	0.674	0.551	0.506

[a] 3448 kN/sq m, 260°C (500 psig, 500°F) steam, condensate returned, boiler efficiency = 0.8.

[b] 30.5 to 45.7 m (100 to 150 ft) average depth - Figure 13.

[c] 1.6 km (1 mi) - Figure 14.

[d] Purchased service and maintenance.

[e] Heat delivered 2394 kJ/kg steam (1,031 BTU/lb steam).

TABLE 13. COST ESTIMATE SUMMARY - ALTERNATE VI

LFG Electricity Generation (Steam Turbine)

Input (cu m/min)	10.20	25.20	50.41	100.69	150.8
Output (kJ/s)[a]	570	1,400	2,800	5,600	8,500
Capital Costs (M$)					
Recovery Subsystem[b]	66	120	228	460	700
Process Subsystem					
Equipment	420	800	1,555	3,060	4,500
Facilities	35	50	90	125	195
Design	29	50	95	180	260
Construction	40	68	100	200	360
Total	524	968	1,840	3,565	5,315
Delivery Subsystem[c]	158	223	298	395	455
Total System	748	1,311	2,366	4,420	6,470
Annual Operating Costs (M$)					
Amortization & Interest Recovery Subsystem	10.1	18.3	34.7	70.1	106.7
Process Subsystem	55.3	102.3	194.4	376.7	561.7
Delivery Subsystem	24.1	34.0	45.4	60.2	69.3
Total A&I	89.5	145.6	274.5	507.0	737.7
Salaries & Wages & S/W Costs	70.5	74.1	78.5	90.7	106.2
Consumables & Parts	10.7	12.0	16.0	27.6	32.5
Utilities	7.0	13.9	23.7	41.5	63.2
Other[d]	7.0	7.0	13.0	20.0	30.0
Total	95.2	107.0	131.2	179.8	231.9
Total Annual Op. Cost	184.7	261.6	405.7	686.8	969.6
Daily Energy Output (MM kJ)	49.2	120.9	241.9	483.8	734.3
No. Annual Days Operation	350	350	350	350	350
Annual Energy Output (10^9 kJ)	17.3	42.4	84.6	169.3	257.0
Cost ($/MM kJ)[e]	10.685	6.174	4.793	4.057	2.824

a Delivered capacity (90% rated capacity) (1 kJ/s = 1 kW).
b 30.5 to 45.7 m (100 to 150 ft) average depth - Figure 13.
c 5 km (3 mi) - Figure 14.
d Purchased service and maintenance.
e kWh = 3600 kJ.

TABLE 14. COST ESTIMATE SUMMARY - ALTERNATE VII

LFG Electricity Generation (Gas Turbine)

Input (cu m/min)	9.20	27.75	53.52	107.05
Output (kJ/s)[a]	410	1,235	3,104	6,213
Capital Costs (M$)				
Recovery Subsystem[b]	65	130	240	480
Process Subsystem				
Equipment	300	800	1,600	3,200
Facilities	15	35	55	100
Design	20	50	90	175
Construction	35	90	175	270
Total	370	975	1,920	3,745
Delivery Subsystem[c]	158	224	333	430
Total System	593	1,329	2,493	4,655
Annual Operating Costs (M$)				
Amortization & Interest Recovery Subsystem	9.9	19.8	36.6	73.2
Process Subsystem	39.1	103.0	202.9	395.8
Delivery Subsystem	24.1	34.1	50.6	65.6
Total A&I	73.1	156.9	290.1	534.5
Salaries & Wages & S/W Costs	36.0	51.9	63.0	90.3
Consumables & Parts	6.3	12.0	16.0	30.0
Utilities	1.6	5.0	9.0	16.0
Other[d]	5.0	12.0	17.0	35.0
Total	48.9	80.9	105.0	171.3
Total Annual Op. Cost	122.0	237.8	395.1	705.8
Daily Energy Output (MM kJ)	35.4	106.7	268.1	536.7
No. Annual Days Operation	350	350	350	350
Annual Energy Output (10^9 kJ)	12.4	37.3	93.8	187.8
Cost ($/MM kJ)[e]	9.809	6.374	4.212	3.758

a Delivered capacity (86% rated capacity) (1 kJ/s = 1 kW).
b 30.5 to 45.7 m (100 to 150 ft) average depth - Figure 13.
c 5 km (3 mi) - Figure 14.
d Purchased services and maintenance.
e kWh = 3600 kJ.

TABLE 15. COST ESTIMATE SUMMARY - ALTERNATE VIII

LFG Electricity Generation (Gas Engine)

Input (cu m/min)	8.86	17.7	53.1	106.2	159.3
Output (kJ/s)[a]	650	1,300	3,900	7,800	11,700
Capital Costs (M$)					
Recovery Subsystem[b]	62	88	240	490	750
Process Subsystem					
Equipment	285	530	1,580	3,000	4,400
Facilities	65	110	270	480	690
Design	30	60	150	270	370
Construction	60	120	320	600	860
Total	440	820	2,320	4,350	6,320
Delivery Subsystem[c]	166	217	344	441	496
Total System	668	1,125	2,904	5,281	7,566
Annual Operating Costs (M$)					
Amortization & Interest Recovery Subsystem	9.4	13.4	36.6	74.7	114.3
Process Subsystem	46.5	86.6	245.2	459.7	667.9
Delivery Subsystem	25.3	33.1	52.4	67.2	75.6
Total A&I	81.2	133.1	334.2	601.6	857.8
Salaries & Wages & S/W Costs	36.0	65.7	170.0	305.8	432.6
Consumables & Parts	7.5	15.0	46.5	90.0	135.0
Utilities	2.0	3.0	8.5	16.5	24.0
Other[d]	10.6	17.5	45.0	85.0	130.0
Total	56.1	101.2	270.0	497.3	721.6
Total Annual Op. Cost	137.3	234.3	604.2	1,098.9	1,579.4
Daily Energy Output (MM kJ)	56.2	112.3	336.9	673.8	1,010.7
No. Annual Days Operation	330	330	330	330	330
Annual Energy Output (10^9 kJ)	18.6	37.1	111.2	222.4	333.5
Cost ($/MM kJ)[e]	7.400	6.315	5.434	4.941	4.736

a Delivered capacity - 100% rated capacity.
b 30.5 to 45.7 m (100 to 150 ft) average depth - Figure 13.
c 5 km (3 mi) - Figure 14.
d Purchased service and maintenance.
e kWh = 3600 kJ.

TABLE 16. COST ESTIMATE SUMMARY - ALTERNATE IX

	LFG Methanol Synthesis	
Input (cu m/min)	98.27	157.32
Output (cu m/day)	45.42	79.49
Capital Costs (M$)		
Recovery Subsystem[a]	452	741
Process Subsystem		
Equipment	4,200	6,120
Facilities	300	400
Design	450	580
Construction	750	1,100
Total	5,700	8,200
Delivery Subsystem[b]	-	-
Total System	6,152	8,941
Annual Operating Costs (M$)		
Amortization & Interest Recovery Subsystem	68.9	112.9
Process Subsystem	602.3	866.5
Delivery Subsystem	-	-
Total A&I	671.2	979.4
Salaries & Wages & S/W Costs	171.3	260.5
Consumables & Parts	35.0	53.0
Utilities	10.0	15.0
Other	35.0	53.0
Total	251.3	381.5
Total Annual Op. Cost	922.5	1,360.9
Daily Energy Output (MM kJ)[c]	795.6	1,392.3
No. Annual Days Operation	300	300
Annual Energy Output (10^9 kJ)	238.7	417.7
Cost($/MM kJ)	3.864	3.258
Cost ($/L)	0.068	0.057

[a] 30.5 to 45.7 m (100 to 150 ft) average depth - Figure 13.

[b] No delivery system required; truck or tank car loading station included in the system.

[c] 17.52 MM kJ/cu m (62,903 BTUs/gal) methanol.

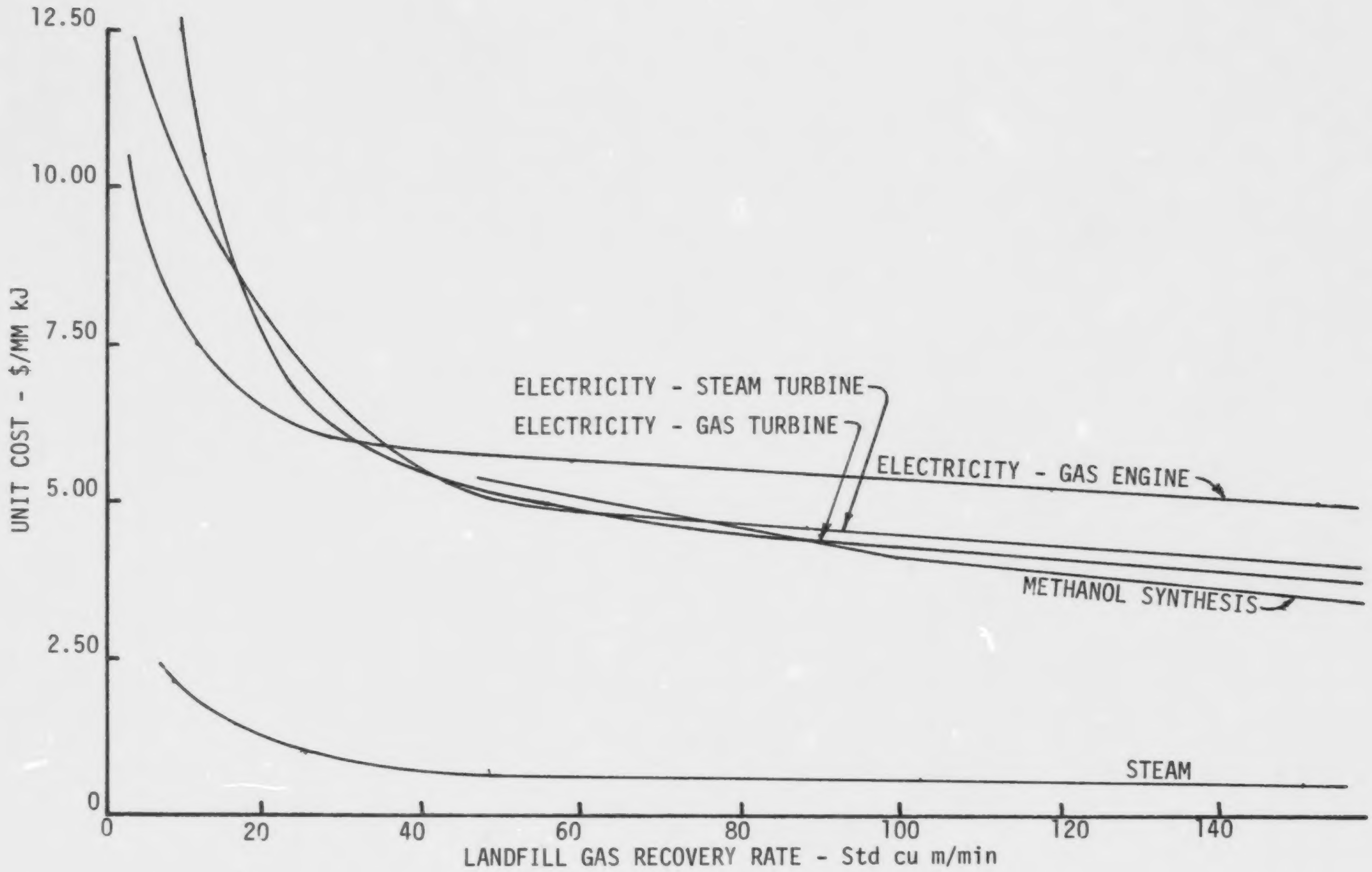


Figure 16. Unit cost of alternative LFG conversion processes.

As can be expected from series or cascaded conversion of process efficiencies, generation of steam is by far the lowest cost process of the three alternative primemovers used for driving a comparable generator. The difference between use of a boiler-steam turbine combination and gas turbine is not significant, while use of gas engine-generator sets is indicated to be somewhat higher in cost beyond a gas recovery rate of about 39.5 std cu m/min (2 MM scf/day), but is somewhat less costly than the two turbines when rates are less than about 29.7 std cu m/min (1.5 MM scf/day). This results because small gas engines have about the same thermal and mechanical efficiency as large units, whereas turbine thermal efficiencies tend to decrease as horsepower is reduced beyond certain levels.

Methanol synthesis is shown on Figure 16 for convenience. For large landfills the cost to produce methanol on an equivalent BTU basis are nearly six times more expensive than dehydrated landfill gas and about twice the cost of LFG with water vapor, carbon dioxide and nitrogen removed.

Using steam priced at $2.55/1.05 MM kJ (MM BTUs) (based on firing natural gas costing $2/1.05 MM kJ (MM BTUs)), steam generation would be a break-even operation for a local government owned and operated facility at a LFG flow rate of about 3.9 std cu m/min (0.2 MM scf/day). For electricity generated and sold at a retail price of $0.05/kw-hr, break-even LFG flows are again about 3.9 std cu m/min (0.2 MM scf/day). For electricity sold at a wholesale rate of $0.03 to local electric utilities, the break-even LFG flow for local government operated facility is about 15.7 std cu m/min (0.8 MM scf/day) for both types of turbine prime-movers and about 5.9 std cu m/min (0.3 MM scf/day) for a gas engine generator set. The cost situation as it relates to process facilities operated by private enterprise is discussed in the next subsection.

Alternative Recovery/Process/Utilization System Economics

Comparative economics were developed for each landfill gas recovery/process/utilization alternative using the cost data provided in Tables 8 through 16, divided into the same two groups: LFG upgrade processes/products and conversion processes/products. Costs and revenues were calculated on an annualized basis assuming 330 days per year for more complex upgrading processes and 300 days for methanol synthesis.

Economic indicators to be used are:

- Gross Surplus or Deficit (Profit or Loss)
- Capital Investment
- Investment Payback Period
- Capital Cost per Unit Daily Capacity (Output)

These indicators permit direct comparison among all alternatives regardless of product, although LFG upgrade products that are fuels should not be compared with conversion products like steam and electricity that are a product of a series of efficiency factors which influence economic results. For example, dehydration of LFG has a process efficiency factor of about 95 percent, steam about 80 percent, electricity generation about 30 to 35 percent, and methanol synthesis about 32 percent. However, to extract the energy from upgraded LFG and methanol, the combustion process imposes another efficiency factor (thermal in this case) that can range from about 20 to 80 percent depending upon method. Consequently, the fuels are compared as a group and steam and electricity are compared as a second group.

All economic indicators are in gross terms; that is, gross surplus or deficit, gross return on investment, gross investment payback period based on revenues less direct operating costs. Because there is no useful way to approximate indirect costs (general and administrative, corporate or parent company overhead, etc.) which can vary from zero to as much as fifty percent of direct costs depending upon the landfill operating entity's relationship to other business organizations (independent operation, subsidiary, division, etc.), no attempt has been made to include indirect expenses. However, it is possible to approximate a normalized annual return on investment after profit and taxes for private enterprise in order that generalized division between acceptable and unacceptable return on investment (ROI) can be established. The expression or minimum acceptable ROI used for this purpose is:*

$$(\text{ROI}) = P \times I = GP = NP + LT + F/SIT$$

where: P = percent of investment returned annually

I = total system investment

NP = net profit at 10 percent of investment

LT = local business property taxes at 50 percent of gross profits

F/SIT = federal and state income taxes at 50 percent of gross profits

GP = gross profit or surplus

Thus, for private enterprise which is to earn an annual net profit of ten percent on its investment, pay both local business property taxes and federal and state income taxes; the expression works out to:

$$GP = P \times I = 0.1\ I + 0.05\ I + 0.5\ P \times I$$

solving for P, $$P = \frac{0.15}{0.5} = 0.3 \text{ or } 30\%$$

For local government ownership and operation of a landfill recovery/processing/utilization system, neither profits or taxes are involved. However, recognizing the risk involved and the uncertainty of the period during which the landfill is likely to produce LFG at a rate sufficient to warrant recovery and processing, it is prudent for local government to establish a reserve for contingency amounting to the equivalent of ten percent of total investment per year. Thus, for government entities:

---

* Similar technique used in Reference 1.

$$P \times I = 0.1\ I \text{ and } P = 0.1 \text{ or } 10\%$$

Calculating the investment payback period for these alternatives on a simple non-compounded basis, the expression is:

$$PP = \frac{I}{(R - OC + A\&I - I)}$$

where: PP = payback period in years

I = capital investment

R = annual revenues

OC = annual operating costs

A&I = annual amortization and interest charges included in OC

I = annual interest charge on total investment

This expression simply substitutes annual interest on the total investment for the constant annual amortization and interest on the decreasing loan balance. Annual operating costs are calculated in order to indicate the amount of surplus funds (revenues less operating costs) that would be available annually to accumulate in a reserve fund until that fund equals total investment.

Landfill Gas Processing Alternatives--

Tables 17 through 20 present summaries of the economics of the four LFG upgrade processes for various LFG recovery rates. The significant indicators are the operating cost per unit of product (million BTUs heating value) which must be sufficiently below the unit price that a reasonable return on investment can be achieved for private enterprise and at least equal to the unit price for government operated facilities. Figure 17 shows the variation of gross return on investment and unit capital cost (dollars per million BTUs of product produced daily) for the four LFG upgrade processes/products.

For private enterprise operations, it is shown that only the LFG dehydration alternative will provide a 30 percent return on investment at a daily gas recovery rate of about 33.4 std cu m/min (1.7 MM scf/day). However, under some circumstances, local gas utilities have indicated a willingness to pay a reasonable return above the cost of producing usable gas. In the near future, natural gas imported from Canada and liquid natural gas imported from Indonesia will be priced at a wholesale rate of about $3.50/

TABLE 17. ECONOMIC ANALYSIS SUMMARY - ALTERNATIVE I

LFG Dehydration and Compression[a]

Daily Energy Output (MM kJ)	331.9	830.1	1660.2	3320.3
No. Annual Days Operations	350	350	350	350
Annual Energy Output(10^9 kJ)	116.2	290.6	581.1	1162.1
Annual Operating Cost (M$)	184.6	273.0	387.3	629.7
Cost ($/MM kJ)	1.589	0.939	0.667	0.542
Revenues				
Rate ($/MM kJ)[b]	1.90	1.90	1.90	1.90
Daily (M$)	0.63	1.58	3.15	6.30
Annual (M$)	220.4	551.3	1102.6	2205.1
Gross Surplus (Deficit)	35.8	278.3	715.3	1575.4
Capital Investment (M$)	636	957	1388	2319
Gross Return on Investment (%)	5.6	29.1	51.5	67.9
Investment Payback Period (Years)	11.1	3.1	1.8	1.4
System Capital Cost/MM kJ Daily Capacity (M$)	1.917	1.157	0.835	0.702

[a] Dehydrated LFG at 17727 kJ/std cu m and 155 kN/sq m (475 BTU/scf, 22.5 psig).

[b] Retail rate - gas delivered to user.

TABLE 18. ECONOMIC ANALYSIS SUMMARY - ALTERNATIVE II

LFG Dehydration and Carbon Dioxide Removal[a]

Daily Energy Output (MM kJ)	700.9	1401.8	2153.3
No. Annual Days Operations	330	330	330
Annual Energy Output(10^9 kJ)	231.4	462.6	710.6
Annual Operating Cost (M$)	359.2	537.4	702.5
Cost ($/MM kJ)	1.552	1.161	0.989
Revenues			
Rate ($/MM kJ)[b]	1.57	1.57	1.57
Daily (M$)	1.10	2.19	3.37
Annual (M$)	362.1	724.2	1112.4
Gross Surplus (Deficit)	2.9	186.8	409.9
Capital Investment (M$)	1740	2772	3792
Gross Return on Investment (%)	0.2	6.7	1.08
Investment Payback Period (Years)	32.7	10.2	7.2
System Capital Cost/MM kJ Daily Capacity (M$)	2.486	1.973	1.765

[a] Upgraded LFG at 35454 kJ/std cu m and 1379 kN/sq m (950 BTU/scf, 200 psig).

[b] Wholesale rate - gas delivered to local gas utility.

TABLE 19. ECONOMIC ANALYSIS SUMMARY - ALTERNATIVE III

LFG Dehydration and Carbon Dioxide and Nitrogen Removal[a]

Daily Energy Output (MM kJ)	616.6	1284.5	2106.7
No. Annual Days Operations	330	330	330
Annual Energy Output(10^9 kJ)	203.5	423.9	695.2
Annual Operating Cost (M$)	555.4	806.8	1051.4
Cost ($/MM kJ)	2.729	1.903	1.512
Revenues			
Rate ($/MM kJ)[b]	1.57	1.57	1.57
Daily (M$)	0.97	2.01	3.30
Annual (M$)	318.5	663.6	1088.3
Gross Surplus (Deficit)	(236.9)	(143.2)	36.9
Capital Investment (M$)	2612	4038	5450
Gross Return on Investment (%)	-	-	0.7
Investment Payback Period (Years)	-	-	28.8
System Capital Cost/MM kJ Daily Capacity (M$)	4.231	3.140	2.590

[a] Upgraded LFG at 36387 kJ/std cu m and 1379 kN/sq m (975 BTU/scf, 200 psig).

[b] Wholesale rate - gas delivered to local gas utility.

TABLE 20. ECONOMIC ANALYSIS SUMMARY - ALTERNATIVE IV

LFG Dehydration, Carbon Dioxide Removal and Propane Blending

Daily Energy Output (MM kJ)	762.1	1524.3	2342.0
No. Annual Days Operations	330	330	330
Annual Energy Output (10^9 kJ)	251.5	503.1	772.9
Annual Operating Cost (M$)	463.3	730.4	991.6
Cost ($/MM kJ)	1.843	1.452	1.283
Revenues			
Rate ($/MM kJ)[b]	1.57	1.57	1.57
Daily (M$)	1.19	2.39	3.67
Annual (M$)	393.7	787.5	1209.9
Gross Surplus (Deficit)	(69.6)	57.1	218.3
Capital Investment (M$)	1802	2847	3877
Gross Return on Investment (%)	-	2.0	5.6
Investment Payback Period (Years)	-	19.9	11.5
System Capital Cost/MM kJ Daily Capacity (M$)	2.362	1.869	1.660

[a] Upgraded LFG at 37320 kJ/std cu m and 1379 kN/sq m (1000 BTU/scf, 200 psig).

[b] Wholesale rate - gas delivered to local gas utility.

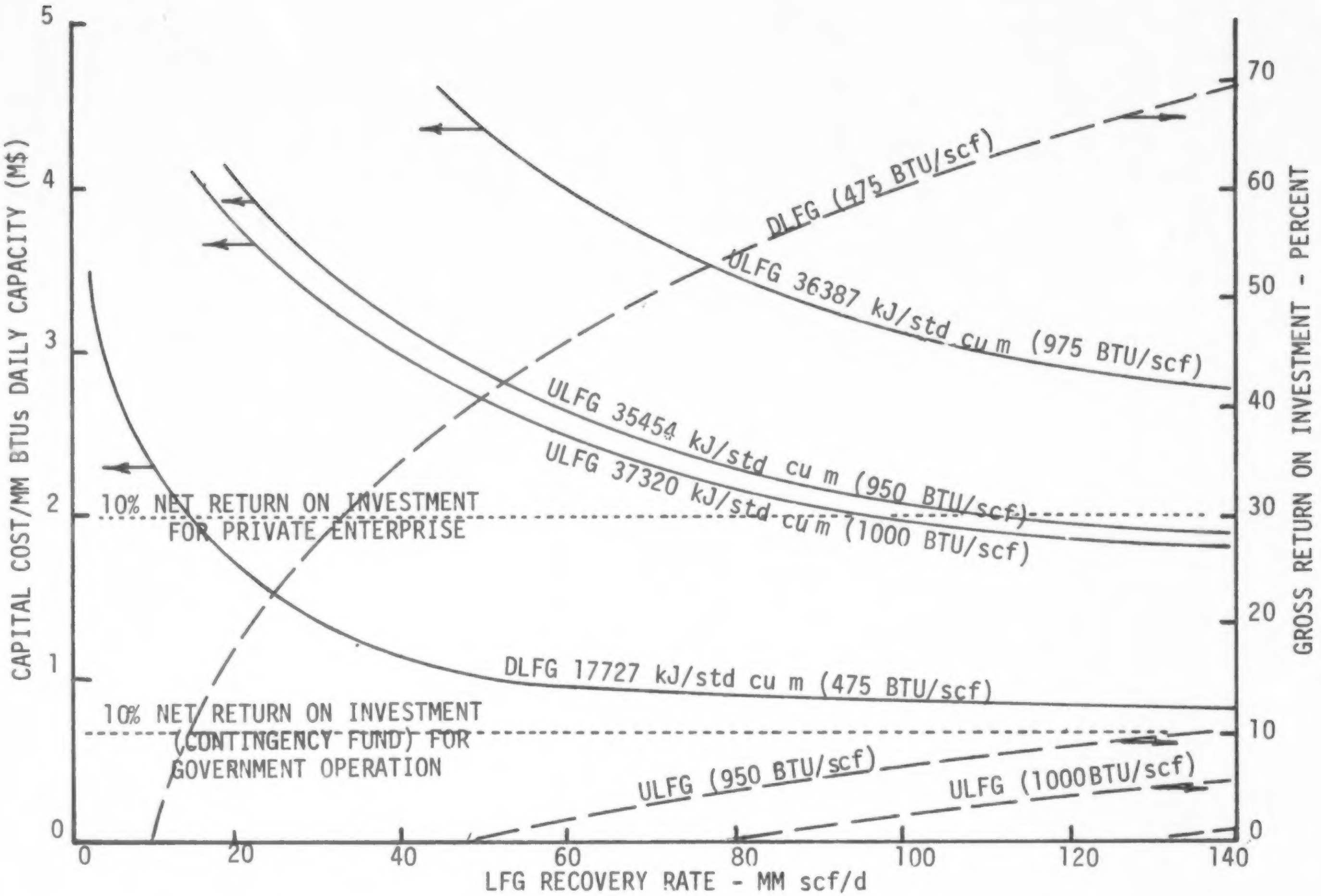


Figure 17. Economic comparison of alternative landfill gas products.

1.05 MM kJ (MM BTUs) which could render one or more of these three LFG upgrade processes economically viable at reasonable gas recovery rates.

For LFG recovery/processing/utilization systems operated by local governments which pay no taxes and require only establishment of a contingency fund (set at ten percent ROI), only dehydration meets this criteria at about 17.7 std cu m/min (0.9 MM scf/day). The other three processes are of questionable practicality if the contingency fund requirement is to be met since required daily flows are well beyond 157.2 std cu m/min (8 MM scf/day). On a break-even basis only and without a contingency fund requirement dehydration with carbon dioxide removal, dehydration and carbon dioxide removal with propane blending, and dehydration with both carbon dioxide and nitrogen removal require about 47.2, 78.6 and 141.5 std cu m/min (2.4, 4, and 7.2 MM scf/day) recovery rates, respectively.

Landfill Gas Conversion Alternatives--

Tables 21 through 25 list economic indicators for steam generation, electricity generation using raw landfill gas as the fuel, and for conversion of LFG of methanol. Figures 18 and 19 show curves of the variation of gross return and investment and unit capital costs against variations in daily LFG recovery rates. For private enterprise which requires a ROI of 30 percent, steam generation and gas turbine generation of electricity with the power sold at retail rates requires daily LFG flows of about 19.65 std cu m/min (1 MM scf). Power generated by a steam turbine which sells at retail rates requires an LFG flow of about 35.4 std cu m/min (1.8 MM scf/day). Electricity generation using a gas engine with power sold at retail rates and gas turbine electricity generation with power sold at wholesale require LFG flows of about 48.2 std cu m/min (2.3 MM scf/day). Electricity generated by steam turbine or gas engine sold at wholesale rates cannot meet the 30 percent ROI requirement at reasonable daily LFG flows.

If local government operates the systems, flow rates necessary to meet the 10 percent ROI requirement for a prudent contingency fund are about 3.9 std cu m/min (0.2 MM scf/day) for gas engine electricity generation sold at retail, 9.8 std cu m/min (0.5 MM scf/day) for both steam generation and gas turbine generated electricity sold at retail, 11.8 std cu m/min (0.6 MM scf/day) for steam turbine generated electricity sold at retail, and about 15.7 std cu m/min (0.8 MM scf/day) for gas turbine electricity sold at wholesale rate. Electricity generated by a steam turbine requires an LFG recovery rate of about 31.4 std cu m/min (1.6 MM scf/day) and power generated by a gas engine requires about 39.3 std cu m/min (2 MM scf/day) when sold at wholesale. Conversion of LFG to methanol does not provide the ROI required by private enterprise at any reasonable LFG recovery rate; for local government with its 10 percent ROI, it requires about 167 std cu m/min (8.5 MM scf/day), or in a break-even situation it requires about 68.8 std cu m/min (3.5 MM scf/day.

In comparing unit capital costs of the various alternatives, one must keep in mind the system losses which occur in the use of the final energy product. Though steam production has the lowest unit capital costs, it is also one of the least efficient forms of energy utilization. Methanol syn-

TABLE 21. ECONOMIC ANALYSIS SUMMARY - ALTERNATIVE V

LFG Medium Pressure/Temperature Steam Generation[a]

Daily Energy Output (MM kJ)	208.6	521.6	1043.2	2086.4	3129.6
No. Annual Days Operations	350	350	350	350	350
Annual Energy Output(10^9 kJ)	73.0	182.6	365.1	730.2	1095.3
Annual Operating Cost (M$)	128.1	176.9	245.8	402.5	553.7
Cost ($/MM kJ)	1.753	0.969	0.674	0.551	0.506
Cost ($/M kg steam)	3.954	2.183	1.519	1.244	1.140
Revenues					
Rate ($/M kg Steam)[b]	5.64	5.64	5.64	5.64	5.64
Daily (M$)	0.49	1.22	2.44	4.86	7.28
Annual (M$)	172.4	426.1	852.3	1702.1	2549.6
Gross Surplus (Deficit)	45.3	249.2	606.5	1299.6	1995.9
Capital Investment (M$)	372	673	1079	2078	3069
Gross Return on Investment (%)	12.2	37.0	55.3	62.5	65.0
Investment Payback Period (Years)	6.4	2.5	1.7	1.5	1.5
System Capital Cost/MM kJ Daily Capacity (M$)	1.78	1.29	1.05	1.00	0.98

[a] 3448 kN/sq m, 260°C steam (500 psig, 500°F), condensate returned from user.

[b] Steam value based on BTUs of LFG used at retail rate of $1.90/MM kJ ($2/MM BTUs) and 2396 kJ/kg (1031 BTU/lb) of steam.

TABLE 22. ECONOMIC ANALYSIS SUMMARY - ALTERNATIVE VI

LFG Electricity Generation (Steam Turbine)

Daily Energy Output (MM kJ)	49.2	120.9	241.9	483.8	734.3
No. Annual Days Operations	350	350	350	350	350
Annual Energy Output (10^9 kJ)	17.3	42.4	84.6	169.3	257.0
Annual Operating Cost (M$)	184.7	261.6	405.7	686.8	969.6
Cost ($/MM kJ)	10.685	6.174	4.793	4.057	2.824
Revenues[a]					
Rate ($/kWh)	0.05	0.05	0.05	0.05	0.05
Daily (M$)	0.68	1.68	3.36	6.72	10.20
Annual (M$)	239.3	587.8	1176.1	2352.1	3570.2
Gross Surplus (Deficit) (M$)	54.6	326.2	770.4	1665.3	2600.6
Rate ($/kWh)	0.03	0.03	0.03	0.03	0.03
Daily (M$)	0.410	1.007	2.016	4.032	6.120
Annual (M$)	143.6	352.7	705.6	1411.3	2142.1
Gross Surplus (Deficit) (M$)	(41.1)	91.1	299.9	724.5	1172.5
Capital Investment (M$)	748	1311	2366	4420	6470
Gross Return on Investment (%)[a]	7.3	24.9/ 6.9	32.6/ 12.7	37.7/ 16.4	40.2/ 18.1
Investment Payback Period (Years)[a]	9.3	3.5/ 9.8	2.8/ 6.3	2.5/ 5.2	2.3/ 4.8
System Capital Cost/MM kJ					
Daily Capacity (M$)	15.199	10.844	9.782	9.137	8.814
Cost/MW Capacity	1312.2	936.4	845.0	789.3	761.2

[a] $0.5/.03 per kWh (1 kWH = 3600 kJ) - retail to user/wholesale to electric utility.

TABLE 23. ECONOMIC ANALYSIS SUMMARY - ALTERNATIVE VII

LFG Electricity Generation (Gas Turbine)

Daily Energy Output (MM kJ)	35.4	106.7	268.1	536.7
No. Annual Days Operations	350	350	350	350
Annual Energy Output (10^9 kJ)	12.4	37.3	93.8	187.8
Annual Operating Cost (M$)	122.0	237.8	395.1	705.8
Cost ($/MM kJ)	9.089	6.374	4.212	3.758
Revenues[a]				
Rate ($/kWh)	0.05	0.05	0.05	0.05
Daily (M$)	0.49	1.48	3.73	7.46
Annual (M$)	172.2	518.6	1303.7	2609.4
Gross Surplus (Deficit) (M$)	50.2	280.8	908.6	1903.6
Rate ($/kWh)	0.03	0.03	0.03	0.03
Daily (M$)	0.295	0.889	2.234	4.473
Annual (M$)	103.3	311.2	782.2	1565.6
Gross Surplus (Deficit) (M$)	(18.7)	73.4	387.1	859.8
Capital Investment (M$)	593	1329	2493	4655
Gross Return on Investment (%)[a]	8.5	39.0/ 23.4	52.3/ 31.4	56.1/ 33.6
Investment Payback Period (Years)[a]	8.1	4.1/ 11.3	2.5/ 5.4	2.3/ 4.7
System Capital Cost/MM kJ				
Daily Capacity (M$)	16.746	12.457	9.298	8.634
Cost/MW Capacity	1446.3	1076	803.2	749.2

[a] $0.5/.03 per kWh (1 kWH = 3600 kJ) - retail to user/wholesale to electric utility.

TABLE 24. ECONOMIC ANALYSIS SUMMARY - ALTERNATIVE VIII

LFG Electricity Generation (Gas Engine)

Daily Energy Output (MM kJ)	56.2	112.3	336.9	673.8	1010.7
No. Annual Days Operations	330	330	330	330	330
Annual Energy Output (10^9 kJ)	18.6	37.1	111.2	222.4	333.5
Annual Operating Cost (M$)	173.3	234.3	604.2	1098.9	1579.4
Cost ($/MM kJ)	7.400	6.315	5.434	4.941	4.736
Revenues[a]					
Rate ($/kWh)	0.05	0.05	0.05	0.05	0.05
Daily (M$)	0.78	1.56	4.68	9.36	14.04
Annual (M$)	257.5	514.6	1544.2	3088.9	4633.0
Gross Surplus (Deficit) (M$)	120.2	280.3	940.0	1990.0	3053.6
Rate ($/kWh)	0.03	0.03	0.03	0.03	0.03
Daily (M$)	0.468	0.936	2.808	5.616	8.424
Annual (M$)	154.5	308.7	926.5	1853.3	2779.8
Gross Surplus (Deficit) (M$)	17.2	74.4	322.3	754.4	1200.4
Capital Investment (M$)	668	1125	2904	5281	7566
Gross Return on Investment (%)[a]	18.0/ 2.6	24.9/ 2.6	28.9/ 11.1	37.7/ 14.3	40.4/ 15.9
Investment Payback Period (Years)[a]	4.6/ 16.0	3.5/ 10.1	2.8/ 7.1	2.5/ 5.8	2.3/ 5.3
System Capital Cost/MM kJ					
Daily Capacity (M$)	11.891	10.022	8.620	7.838	7.486
Cost/MW Capacity	1027.7	865.4	744.6	676.9	767.7

[a] $0.5/.03 per kWh (1 kWH = 3600 kJ) - retail to user/wholesale to electric utility.

TABLE 25. ECONOMIC ANALYSIS SUMMARY - ALTERNATIVE IX

LFG Methanol Synthesis

Daily Energy Output (MM kJ)	365.9	795.6	1392.3
No. Annual Days Operations	300	300	300
Annual Energy Output(10^9 kJ)	109.8	238.7	417.7
Annual Operating Cost (M$)	563.7	922.5	1360.9
Cost ($/MM kJ)	5.146	3.864	3.258
Cost ($/L)	0.090	0.068	0.057
Revenues			
Rate ($/L)	0.092	0.092	0.092
Daily (M$)	1.93	4.20	7.35
Annual (M$)	675.5	1470.0	2572.5
Gross Surplus (Deficit)	74.0	337.5	844.1
Capital Investment (M$)	3755	6125	8941
Gross Return on Investment (%)	2.0	5.5	9.4
Investment Payback Period (Years)	23.1	12.5	8.4
System Capital Cost/MM kJ Daily Capacity (M$)	10.261	7.699	6.421
Cost ($/cu m)	179.74	134.85	112.50

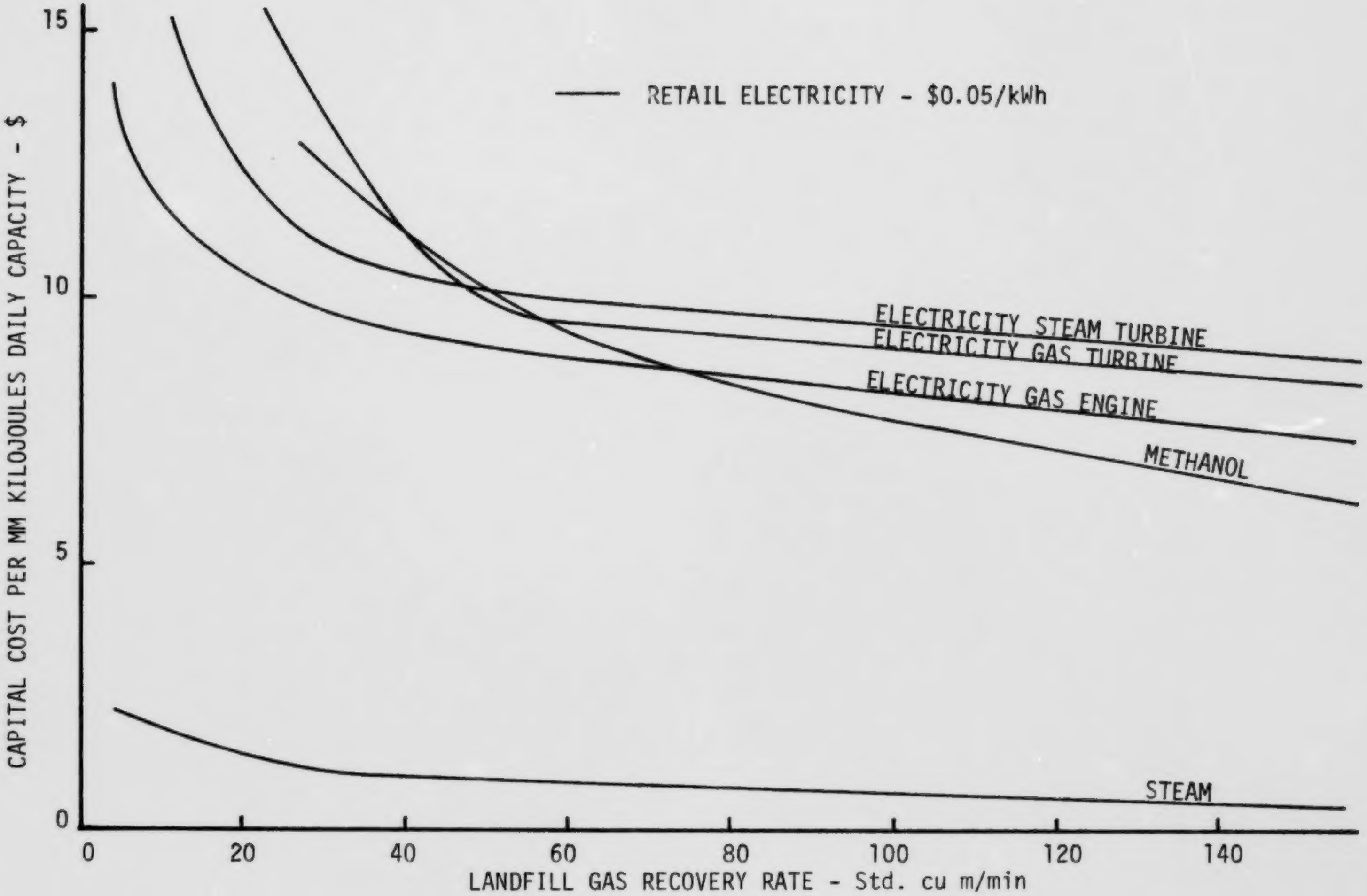


Figure 18. Economic comparison of alternative LFG conversion processes.

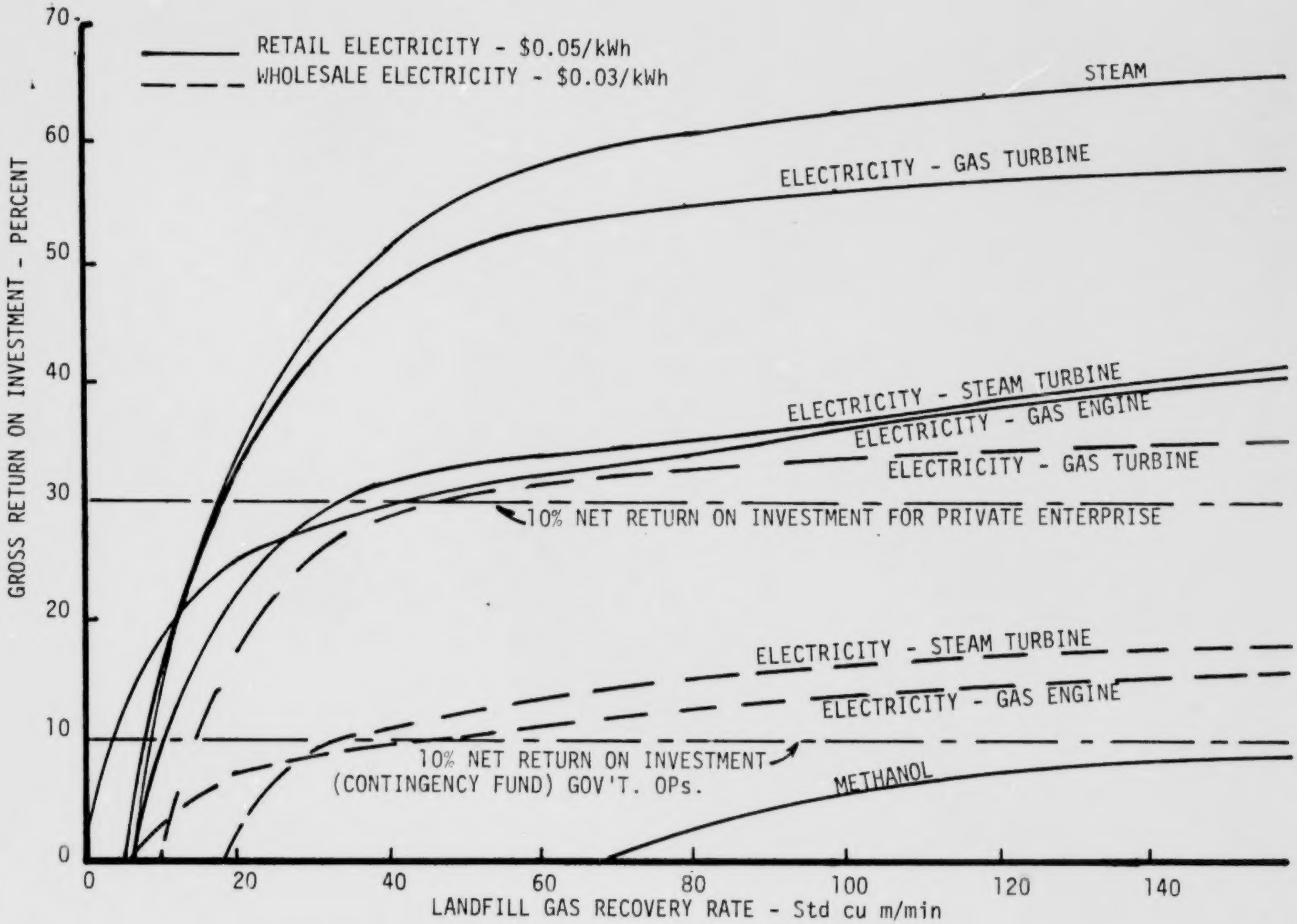


Figure 19. Economic comparison of alternative LFG conversion processes

thesis, which has a much higher unit capital cost, produces a liquid fuel which can be converted to usable energy with considerably greater efficiency.

SUMMARY

Comparisons of alternative uses for landfill gas and the processes required to produce the alternative products suggest that:

1. Use of dehydrated landfill gas as a supplementary or replacement fuel shows the greatest promise from the standpoints of technical and economic feasibility, applicability to the broadest variety of landfill sites in terms of their volumes and gas flow rates, and suitability for development and operation by either private enterprise or local government entities.

2. Further upgrading of LFG (removal of carbon dioxide or both carbon dioxide and nitrogen) is presently too expensive to be feasible for private enterprise and is feasible for local governments only on a break-even economic basis for landfills of reasonable size and when sold to local utilities at wholesale prices. (Except for unusual circumstances that enhance the financial picture.)

3. Generation of steam or electricity using raw LFG as the fuel is technically and economically feasible at reasonable LFG recovery rates for both private enterprise and local government when sold to users at retail prices.

4. Any of the three prime methods used to generate electricity using raw LFG as fuel can be economically feasible for local government while only electricity generated by gas turbines is economically feasible for private enterprise when sold to local utilities at a wholesale price.

SECTION 6

LANDFILL DESIGN AND OPERATIONAL TECHNIQUES FOR ENHANCEMENT OF GAS GENERATION AND RECOVERY

This section reviews current state of the art landfill site selection criteria, design principles and operational techniques that show promise of enhancing landfill gas generation and recovery. Desirable characteristics, principles and techniques are briefly discussed and evaluated as to probable applications, practicality, typical likely incremental costs and probable results, both favorable and unfavorable.

Most of the information presented in this section pertains to the siting, design and operation of new landfills planned for LFG recovery and utilization. However, some of the operating techniques should be applicable to completed or currently operational landfills which are candidates for LFG recovery systems.

Production of leachates in landfills and percolation of these high BOD and COD liquids into the ground water table must be prevented. Thus, site selection, design and operational techniques must be compatible with proper leachate control. Desirable landfill conditions are those which prevent leachate from reaching ground water tables, minimize the production of leachate through proper surface drainage and the use of impervious cover materials, and prevent landfill gas migration in any direction. However, there are few sites that present ideal topographical, geological and soil conditions so design measures and operational techniques often must be used to minimize the pollution potential of landfills.

Certain measures for enhancement of gas generation may be in opposition to control of leachate production and percolation. For example, available data suggests that for optimal gas generation, the emplaced waste should have at least a 50 percent moisture content. Because landfill gas is typically at or near saturation, this moisture content must be maintained by the introduction of water from the surface or outside the landfill. This dictates the use of permeable cover material that permits percolation of surface water, but at the same time prevents the desirable ventilation of landfill gas or inhalation of air during recovery. A relatively wet solid waste mass emplaced in a landfill tends to accelerate leachate formation and drainage to the bottom of the landfill which, in turn, tends to increase the hydraulic pressure that can increase percolation through the bottom of the landfill into the ground water table. Thus, there can be a basic conflict between minimization of leachate formation and maintenance of optimal conditions for landfill gas formation.

Various types of landfill designs that respond to variations in prevailing geology, soils and terrain are not covered because this subject is adequately delineated in a number of EPA documents.[55-61] Also there are several recent reports on the subjects of gas and leachate control.[4-6] Accordingly, the emphasis of this section is on a discussion of the suitability and applicability of special measures that are believed to have potential for enhancing gas generation and collection in order to improve the likelihood of economic viability for landfill gas recovery/processing/utilization projects.

Material presented herein is organized into three divisions:

1. Landfill site selection and characteristics
2. Landfill design
3. Landfill operational techniques

LANDFILL SITE SELECTION AND CHARACTERISTICS

The major criteria governing the selection of a new landfill site that is to incorporate LFG recovery/processing/utilization are essentially the same as for any landfill. Additional criteria are imposed, however, in order to minimize the costs of the recovery system and enhance both gas generation and gas characteristics to the extent practical.

Size and Geometry

To take advantage of economies-of-scale characteristics of continuous process systems, the site should be as large as possible. Figure 20 shows curves of LFG recovery rates as functions of in-place solid waste quantities and daily LFG production. For example, based on typical landfill parameters (compacted waste density 592 kg/cu m (1000 lb/cu yd), 20 percent cover material by volume), fill areas per million tons of emplaced solid waste are:

Amount of waste in-place	Average depth	Fill area MM tons S.W.	Perimeter area
0.9 MM t (1 MM T)	15.2 m (50 ft)	12.5 ha (31 ac)	17.4 ha (43 ac)
0.9 MM t (1 MM T)	30.5 m (100 ft)	6.5 ha (16 ac)	12.5 ha (31 ac)
0.9 MM t (1 MM T)	45.7 m (150 ft)	4.5 ha (11 ac)	10.1 ha (25 ac)

The perimeter area is an additional area for screening, noise attenuation and separation of the fill area from adjacent land uses. At a minimum, it should be about 122 m (400 ft) in width. As the fill area increases, the ratio of perimeter area to the fill area decreases.

Figure 16 in Section 4 showed that unit capital and operating costs of LFG recovery and basic dehydration became nearly constant above 544t (600 T) per day equivalent daily capacity. This equals about 77825 std cu

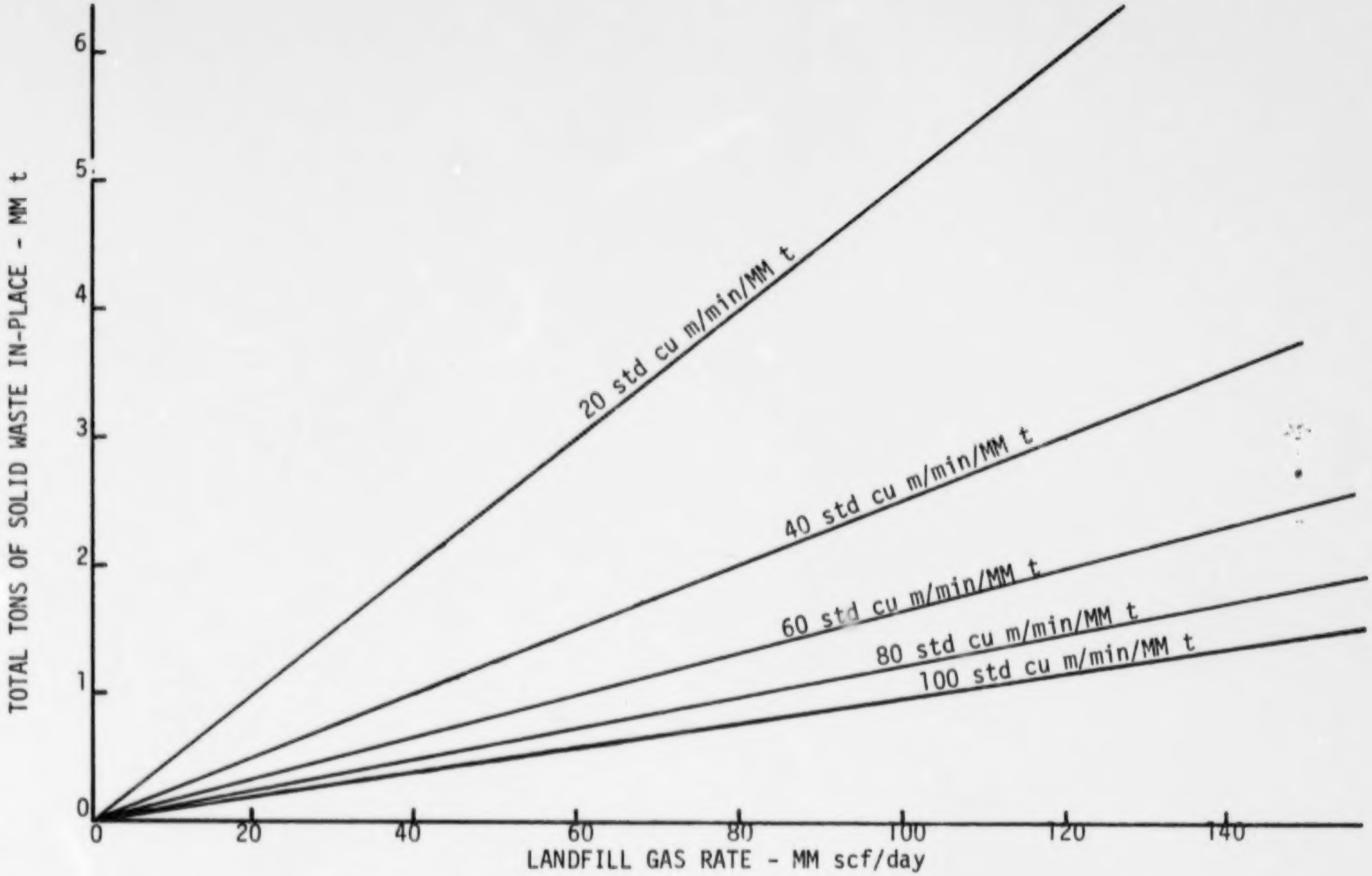


Figure 20. Landfill gas generation rates for various solid waste quantities in-place.

m (2.75 MM scf) of LFG per day (1 MM scf/day is equivalent to a capacity of 217.4 T/day). However, the rate of increase in unit capital and operating costs as capacity decreases is gradual so that desirable landfill size for LFG recovery/processing/utilization falls in the range of 35.4 to 54 std cu m/min (1.8 to 2.75 MM scf/day). This equates to a fill area ranging from 2.27 to 3.44 MM t (2.5 to 3.8 MM T) of solid waste in place (using a nominal LFG generation rate of Figure 20 of 15.6 cu m/min/MM t (500 cfm/MM T which relates to the generally accepted 0.13 scf LFG/lb of solid waste/yr). These LFG recovery rates and quantities of solid waste in place are the basis for the fill and perimeter areas for minimal desirable landfill sizes listed in Table 26. Also listed are the estimated unit costs taken from Figure 15 in Section 5.

Smaller landfills also can be mined for LFG but the unit cost of dehydrated LFG begins to rise more rapidly. For example, a fill area half the size of the low end of the desirable range, 17.7 std cu m/min (0.9 MM scf/day recovery rate) is estimated to have a unit cost of $1.48 per 37.32 MM kJ (MM BTUs).

Also figuring strongly into the unit capital and operating costs of LFG recovery/processing/utilization systems is the average depth of the fill area. Costs increase as the average fill depth decreases primarily because of the more extensive and thus more costly recovery system as depicted in Figure 13 of Section 5. It is highly desirable that the site selected for a new landfill be designed and developed for as deep a fill area as possible for LFG recovery/processing/utilization.

The surface configuration of landfills varies widely. However, it is desirable for LFG recovery systems that the fill area be approximately square or rectangular and the side dimensions be multiples of about 69 to 76 m (225 to 250 ft) for optimal coverage of recovery well influence areas.[2,25,44] The geometry of fill areas is more critical for small landfills than for large ones.

Other Desirable Characteristics

The presence of a highly impermeable geological structure underlying the fill area is particularly important for those landfills planning LFG recovery systems. It is highly desirable to maintain a relatively high moisture content in the emplaced solid waste in order to enhance gas generation, either by the regular addition of water to the fill area, leachate recycling or possibly both. The impermeable underlying structure should slope to one or more low points so that leachate can drain, be collected in sumps and be removed or recycled. While it is often possible to shape the bottom of the fill area as desired, should the underlying structure be rock or semi-rock, the cost might be high for re-sloping it to the desired contours.

The sides of the fill area similarly should be composed of highly impermeable materials to contain leachates and landfill gas.

TABLE 26. MINIMUM AREAS DESIRABLE FOR LANDFILL GAS RECOVERY PROJECTS

Average fill depth (m)	Solid waste quantity (MM t)	Daily LFG recovery rate (std cu m/day)	Fill area (ha)	Minimum perimeter area (ha)	Total landfill area (ha)	Estimated product cost ($/MM kJ)
15.2	2.27	50976	31.36	27.32	58.68	0.93
15.2	3.45	77880	47.67	33.67	81.34	0.74
30.5	2.27	50976	16.19	19.63	35.82	0.93
30.5	3.45	77880	24.61	24.20	48.81	0.74
45.7	2.27	50976	11.13	16.27	27.40	0.93
45.7	3.45	77880	16.92	20.07	36.99	0.74

Based on mid-range gas generation of 22481 cu m/day/MM t (0.72 MM scf/day/MM T) in-place.
Estimated unit costs for LFG recovery and dehydration from Figure 15, Section 4.

The topography of the site should be such that natural surface drainage can be readily controlled and the fill surface contoured to provide controlled drainage of precipitation to provide the desired level of percolation into the fill for moisture control.

While the availability of suitable cover material is a criterion for the selection of any landfill site, this is a particularly important factor for a site that is to incorporate a LFG recovery system. The cover material must be highly impermeable if the additional cost of importing material from another site or adding chemicals to the soil to decrease its permeability are to be avoided.

Pertaining to the selection of a landfill site that is to include LFG recovery and processing: There should be one or more multiple large fuel users in the immediate vicinity of the site (e.g., industry, institutions, power plants, etc.) preferably within a radius of 8 km (5 mi), or there should be a natural gas transmission main or electricity transmission line within a few kilometers (miles) of the site. It would be useless to select and develop a landfill site for LFG recovery/processing/utilization if there were no large fuel/energy product users in the immediate vicinity that were interested in purchasing and using the product when it became available. Accordingly, it is well to survey potential users and alternative sites as part of the survey. This survey is necessary not only for basic site selection, but to determine which of the alternate LFG fuel/energy products can be sold and thus which of the alternative process systems should be implemented.

LANDFILL DESIGN

There are a number of alternative approaches to the planning and design of a landfill that is to incorporate LFG recovery and processing which apply under different site conditions. In general these approaches are not greatly different from those applied to a landfill which is not expected to incorporate an LFG system, although certain aspects become more important in order to optimize LFG generation and make recovery as efficient and complete as possible.

For the site on which a LFG system is to be added, solid waste cells should be located in a manner that will facilitate an efficient recovery well and collection pipeline complex. All fill areas should be contiguous and the final fill area contour should be sloped for drainage purposes. This applies to both trench or area method landfills. Use of stepped contours in final grading of fill areas on steep slopes can be used as necessary and fill area plateaus at different elevations also can be accommodated as appropriate to the original terrain contours. However, use of these design features will increase the cost of the recovery system, especially the collection pipelines, manifolds and pressure balancing valves.

A major design difference between a landfill with LFG recovery and a standard fill is in the area of leachate collection and control. While leachate can be controlled in a standard landfill by minimizing the entrance of water into the fill, it is desirable for water to percolate into the fill to enhance gas generation. This will increase leachate generation well beyond the amount otherwise formed, and a system of bottom drainage channels, collection sumps and recovery wells will be required in the basic landfill design and development plan. This system will be similar to that included in a landfill that is to receive hazardous liquids and sludges as well as solid waste, but usually not required for a fill limited to municipal solid waste unless the underlying geology and/or water table height are unfavorable.

Various alternative approaches to design of landfills with LFG systems are outlined and discussed below. Each alternative is evaluated and approximate costs stated followed by a cost-effectiveness example, where information is available.

Site Lining

Gas and leachate migration from a landfill can be controlled by the use of appropriate barriers within the confines of the site. The objective of placing suitable barriers under and along the sides of the fill area is to prevent, or at least, minimize the outward movement of gas and leachate beyond site boundaries. Use of impermeable barriers also tends to increase the potential for recovery of landfill gas. Low permeability materials used can be natural, such as certain types of soil; or synthetic, such as plastic or rubber membranes. The placement of low permeability soil under and along the sides of the site can be accomplished with small additional effort and cost in areas where suitable materials are available. However, in many areas of the nation, suitable soils have to be purchased and transported distances ranging from significant to prohibitive.

Some fine clays have liquid permeabilities as low as 10^{-8} cm/sec. A layer of more common fine clay could have a permeability as low as 10^{-7} cm/sec permeability, but sandy silt is considerably more permeable. A permeability of 10^{-4} cm/sec is equivalent to 7.5 cm (3 in) of water seepage per day. The California State Water Resources Control Board requires a minimum permeability of 10^{-6} cm/sec for a site receiving decomposable (organic) materials.

Table 27 lists permeabilities of some soils and clays. For soils available in the immediate vicinity of the landfill, the cost of installing the barrier is similar to a normal grading operation, which averages between $1.96 to $2.62/cu m($1.50 to $2.00/cu yd). For a 15 cm (6 in) layer of soil, the cost would be approximately $.36/sq m ($.30/sq yd). Importation of suitable soils over even a fairly short haul distance could double the cost of installing the barrier.

When materials must be imported, commercially produced soil sealants or plastic film barriers might become cost competitive alternatives. Commercially processed bentonite clays which expand considerably when wetted are available in powdered or granulated form. Mixing this material with normal soils can produce a very low permeability material. For a 15 cm (6 in) layer, sealant at 10 to 15 kg/sq m (2 to 3 lbs/sq ft) would be re-

TABLE 27. PERMEABILITY COEFFICIENTS FOR SOILS OF DIFFERENT TEXTURE

Material	Permeability coefficient (cm/sec)
Coarse sand	1.39×10^{-1}
Sand	1.39×10^{-2}
Fine sand	5.6×10^{-3}
Very fine sand	2.8×10^{-3}
Loamy sand	1.4×10^{-3}
Sandy loam	2.8×10^{-4}
Loam	5.5×10^{-5}
Clay	1.4×10^{-6}

Source - Reference 29.

quired. Installed costs of American Colloid Company's VOLCLAY product range from \$1.79 to 2.39/sq m (\$1.50 to \$2.00/sq yd). A protective layer of soil would be required above the barrier in most cases because this barrier is not very resistant to physical forces resulting from vehicle traffic, precipitation or drainage water. A suitable protective layer, using a variety of materials, could be installed at normal grading costs of about \$.36/sq m (\$.30/sq yd); thus, the total barrier cost ranges from \$2.15 to \$2.75/sq m (\$1.80 to \$2.30/sq yd).

The permeability factors discussed above are for water percolation. Gas has an even greater capacity for permeating soils than does water. However, since landfill gas is much less dense than water and slightly lighter than air, it is more likely to migrate upwards if this is the path of greater permeability. Typical compacted solid waste has a permeability range (depending upon moisture content) of 10^{-3} to 10^{-4} cm/sec, considerably more permeable than a good soil barrier. If allowance is made for upward migration so that the downward pressure gradient does not become large (which would be the case for a landfill gas recovery system), suitable liquid-soil barriers should be able to prevent passage of the gas.

Another approach to a low-permeability membrane is a synthetic film liner. Polyethylene (PE), chlorinated polyethylene (CPE), chlorosulfonated polyethylene (hypalon), polyvinyl chloride (PVC), butyl rubber, and ethylene propylene rubber (EPDM) are some of the more common materials used for liners. The procedure used when installing a membrane is as important as selecting the membrane material. Preparation of the base, seam joining of membrane strips and application of a protective cover layer are all critical to the effectiveness and life of the membrane. If seaming of membrane strips is performed by qualified personnel using the proper equipment and procedures, the base material is free of rocks and debris, and care is taken not to puncture the membrane while placing a protective layer of sand or clean soil over it, any of these membranes will prevent liquid and gas penetration for substantial hydrostatic heads and gas pressures. In addition, a membrane material should be selected that will not be affected by landfill leachate.

Table 28 lists costs of landfill liner materials. The cost of installing membranes is considerably higher than soil barriers. Estimates range from \$1.55/sq m (\$1.30/ sq yd) for 10 mil thick polyethylene film (minimum thickness) to \$6.00/sq m (\$5.00/sq yd) for 30 mil butyl. A range of \$2.15 to \$3.23/sq m (\$1.80 to \$2.70/sq yd) installed has been estimated for 20 mil polyvinyl chloride, a commonly used membrane material. This does not include the cost of base preparation or the protective layer above the membrane. Use of a low-permeability barrier enhances environmental protection aspects of a landfill by minimizing both gas and leachate migration. The cost-benefits of a barrier, however, need to be weighed against the additional gas revenues that would be gained as a result of the additional LFG recovered.

A hypothetical landfill, 40 ha (100 ac) in area, with an average fill depth of 15.2 m (50 ft) is used for an approximate cost-benefit analysis.

TABLE 28. COST FOR VARIOUS SANITARY LANDFILL LINER MATERIALS[*]

Material	Installed cost[†] ($/sq m)
Polyethylene (10 - 20[‡] mils [§])	1.51 - 2.42
Polyvinyl chloride (10 - 30[‡] mils)	1.96 - 3.61
Butyl rubber (31.3 - 62.5[‡] mils)	5.44 - 6.70
Hypalon (20 - 45[‡] mils)	4.82 - 5.12
Ethylene propylene diene monomer (31.3 - 62.5[‡] mils)	4.07 - 5.73
Chlorinated polyethylene (20 - 30[‡] mils)	4.07 - 6.63
Paving asphalt with sealer coat (5 cm)	2.01 - 2.85
Paving asphalt with sealer coat (10 cm)	3.93 - 5.44
Hot sprayed asphalt (4.53 L/sq m)	2.51 - 3.35
Asphalt sprayed on polypropylene fabric (100 mils)	2.11 - 3.13
Soil-bentonite (24 kg/sq m)	1.21
Soil-bentonite (47.7 kg/sq m)	1.96
Soil-cement with sealer coat (15 cm)	2.09

[*] Source: Haxo, H.E. Jr. Evaluation of liner materials. U.S. EPA Research Contract 68-03-0230. October, 1973. Adjusted to 1977 $.

[†] Cost does not include construction of subgrade nor the cost of earth cover. These can range from $1.18 to $1.97/sq m/m of depth.

[‡] Material costs are the same for this range of thickness.

[§] One mil = 0.001 inch = 0.0254 mm.

Assumptions used range from conservative to optimistic. Assuming 474 to 710 kg/cu m (800 to 1200 lbs/cu yd) in-place density of waste and 156 to 312 std cu m of LFG recovered per metric ton (5000 to 10000 scf/T) of waste emplaced during the economic collection period, the total generation of methane at 45 percent to 55 percent concentration would be from 1.7×10^8 to 6.2×10^8 cu m (5.9×10^9 to 2.2×10^{10} scf) of methane assuming a 75 percent recovery efficiency. Placing an impermeable barrier below, on the sides and on top of the landfill could increase the yield to 90 percent or from 2×10^8 to 7.4×10^8 cu m (7.0×10^9 to 2.6×10^{10} scf) of methane. This incremental yield of from 0.34×10^8 to 1.1×10^8 cu m (1.2×10^9 to 4×10^9 scf) of methane at $2.00/37.32 MM kJ (MM BTUs) would provide additional revenues of between $2.3 and $8.6 million.

The costs for a low-permeability barrier would be as low as $.36/sq m ($.30/sq yd) where good quality clay was readily available within (or adjacent to) the landfill and as high as $3.95/sq m ($3.30/sq yd) for a high-quality membrane at a site which required considerable base preparation. For the 40 ha (100 ac) landfill example, 93645 sq m (112000 sq yd) of barrier would be necessary to line the sides and bottom for a cost range of $33,000 to $370,000. (Note that this range would be higher for a shallower landfill and lower for a deeper landfill because the ratio of barrier area to landfill volume is higher and lower, respectively.

Thus, it appears that there may be substantial economic benefit due to increased LFG recovery.

Moisture Control

Although placement of a low permeability barrier as the final cover layer prevents or reduces LFG losses by vertical migration, this approach tends to prevent moisture infiltration. Data presented in Section 4 suggests that a minimum of 50 percent moisture content is needed to enhance gas generation. A low permeability cover thus, may retard LFG generation by preventing needed moisture from reaching the active fill areas. Methods for preventing gas escaping through the cover barrier while at the same time allowing moisture infiltration, is therefore an item of primary concern.

There are three basic methods for allowing moisture infiltration while preventing gas exfiltration. Use of a water distribution system to introduce water below the low permeability soil or membrane barrier is one approach. A second approach is to use a soil barrier that will allow water to infiltrate but will prevent gas migration. The third approach involves overdesigning the gas collection system to prevent migration without the need for a low permeability barrier. Each method is discussed and evaluated and a cost-effectiveness example presented.

A water distribution system to introduce water below the low permeability soil cover or membrane is a positive and readily controllable method for providing moisture to a landfill. The distribution system resembles a field crop irrigation system with main supply lines passing through the cover at certain locations to connect to a system of distribution piping located immediately below the cover. A key design problem for this type of system is the method used for sealing the main line penetrations through the cover. Boots with sufficiently large flange areas and positive clamps to seal the boot around the pipe have proven adequate in similar applications.

Both the cost and the effectiveness of water distribution depend on the degree to which the distributed wastes are effected. Achieving an even water release pattern without concentrated wet spots requires closely spaced release points and thus a large quantity of piping. The optimization of cost and effectiveness of the system is the major design requirement.

A distribution piping system consisting primarily of 2.5 and 5 cm (1 in and 2 in) polyvinyl chloride (PVC) pipe costs approximately $4.10/m ($1.25/lin ft) for pipe and installation. For a hypothetical fill area of 40 ha (100 ac) distribution pipe lines spaced 15.2 m (50 ft) apart with 1750 delivery heads located 15.2 m (50 ft) apart, would require roughly 27430 m (90000 ft) of pipe costing about $112,000. At an installation cost of $.20 per delivery head, the cost of the heads would be insignificant compared to the pipe cost. With a high impermeability cover, evaporation losses would be low and water quantity and pump requirements would be small. Pumping costs would therefore be insignificant compared to the piping. A total cost of $125,000 has been estimated for a 40 ha (100 ac) area using this approach.

A semi-permeable soil barrier kept moist is another approach to controlling the passage of water and gas. If a silty or sandy soil is kept near moisture saturation, it would constitute a form of barrier to the outward migration of landfill gas because the water fills the voids between the soil particles. Although gas under sufficient positive pressure would still be able to escape through the soil cover, using this approach in conjunction with adequate gas withdrawal negative pressure should prove effective. The saturated soil would allow rainfall or artificially distributed water to pass through but act as a barrier to gas passage.

In order to keep the soil layer saturated it would be helpful to treat the soil with a humectant. Commercially available humectants in liquid or powder form are often used in landscaping projects to improve the moisture retention of the soil for plant irrigation purposes and in grading projects to improve the ability of water to penetrate the soil for compaction purposes. Spraying approximately 61 l/ha (40 gal/ac) of humectant results in a soil layer that has good water retention characteristics. One vendor provides a product at a cost of $.80/l ($3.00/gal). It is possible to apply this humectant to a 40 ha (100 ac) site for about $12,000 plus a modest labor cost. The bulk of the cost of this approach would be in keeping the cover soil saturated to make up for evaporative losses. This would require an irrigation system costing $50,000 to $100,000 or the use of several water trucks at a cost of about $150 each per day. The practical effectiveness of this approach is limited, particularly in dry areas of the country. As soon as a portion of the cover becomes dry, gas would escape from the landfill at that point.

The third approach consists of "pumping" the landfill in a manner which develops a slight negative pressure immediately below the cover. This would allow the use of permeable cover for water infiltration. However, it is difficult to control gas pressure with required precision over large areas, and to prevent excess negative pressures in some areas from drawing in air. This is particularly true if the landfill is relatively shallow. The area of influence of a gas well approximates a pear-shaped [illegible] in configuration. The radius of influence of the well in the horizontal plan is directly related to the depth of influence in the vertical plane. If a well is pumped enough to influence a large area in the horizontal plane, the vertical influence will be large and the well must be relatively deep to avoid ingesting air from above the permeable cover. Thus, a large number of closely spaced wells pumped at a moderate rate to recover all the gas and pervent vertical migration is required. In addition, the sides of the landfill would have to be lined to prevent ingesting air from natural soil beyond the edge of the landfill.

Using the hypothetical 40 ha (100 ac) 15.2 m (50 ft) deep fill area landfill, the required spacing of the wells can be determined as a function of the radius of influence of the wells. The radius of horizontal influence of recovery wells will vary from landfill to landfill with the permeability of the waste. Solid waste permeability depends on composition, degree of compaction, and typically is about 0.001 to 0.0001 cm/sec which is about that of loamy sand. The design of the well, the depth of the fill and the amount of vacuum applied also determine the radius of influence. For the purpose of this estimate, the horizontal radius of influence that will avoid air intrusion is taken to be 22.9 m (75 ft) for a 12.2 m (40 ft) deep fill. Thus, the wells would have to be located on about 45.7 m (150 ft) centers. 196 wells would be needed to completely cover the landfill. The hypothetical landfill would produce about 45.8 cu m/min (1620 cu ft of gas/min), based on 15.6 cu m/min/MM t (500 cu ft/min of gas/MM T) of in-place waste. Thus, each well would be delivering about 0.28 cu m/min (10 cfm) of LFG. The possibility of air intrusion or the existence of small pockets of aerobic decomposition would still not be totally eliminated.

To put this collection system in perspective, the same landfill using a low permeability cover material such that air infiltration would not be a problem, could be expected to have a horizontal radius of influence for each well of 30.5 m (100 ft). Locating the wells on 61 m (200 ft) centers would result in 100 wells each producing about 0.45 cu m/min (16 cfm). The difference in cost of the two systems would be substantial. A 12.2 m (40 ft) deep well costs from $2,000 to $4,000 to drill and install. Collection piping costing approximately $23/m ($7.00/ lin ft) is required for the multiple-well system. The total costs for the two systems, 100 and 196 wells, would be about $465,000 and $810,000 respectively, a difference of $345,000.

For the 40 ha (100 ac) 15.2 m (50 ft) deep fill, the first method would cost about $115,000, the second method $50,000 to $100,000 for a distribution system or about $500,000 per year for water spray trucks,and the third method about $345,000 more than the well system that otherwise would be required.

The increase in gas generation expected to result from maintaining waste moisture at or above 50 percent compared with the typical solid waste moisture content of 15 to 25 percent as emplaced cannot be estimated with adequate accuracy because information is lacking on this subject. It is clear, however, that increased moisture content results in enhanced gas generation. An approximation of the cost-effectiveness of any of the three measures can be made. Assuming a total gas generation quantity between 156 to 312 std cu m/t (5000 and 10000 scf/T) of emplaced solid waste, 474 to 710 kg/cu m (800 to 1200 lbs/cu ft) implace density; increasing recovery effectiveness from 75 to 90 percent would produce incremental gas sales revenues between \$2.3 and \$8.6 million (same example used in the preceding subsection). Thus, all but the spray truck method would be cost-effective in this example, even at the lower end of the additional revenue range.

Leachate Collection and Recycling

Collecting and recycling leachate back into the fill is another possible way to control and maintain adequate moisture content and control the pH to enhance gas generation. A pH range from 5.5 to 9.0 is generally acceptable for gas production, but optimal pH is near 7.0 so that 6.0 to 8.0 probably is a more desirable range. Recycling the leachate would tend to provide nutrients to the gas generating organisms, maintain desired pH on a more even level throughout the fill as well as help maintain the desired moisture level.

Leachate recycling is analogous to activated sludge being fed back into the aeration tank influent in a sewage treatment plant.

An integral part of the leachate recycling system would be monitoring of leachate composition and pH. In order to maintain pH within the desired range, it may be necessary to add acidic or alkaline substances compatible with anaerobic methane formers, or remove by appropriate treatment, any components detrimental to gas formation.

The landfill fill area should be designed for leachate collection and removal. In addition, a suitable irrigation distribution pipeline for maintenance of moisture levels would be needed although probably not as capacious a system and thus not as costly. Details of leachate recycling and appropriate treatment can be found in a 1975 EPA report.[4]

Gas Recovery Well Design and Spacing

The first step in the design of a landfill gas recovery system is to survey the landfill or its completed areas to determine if LFG is being generated. This can be done by using portable methane sensing instruments or by encapsulating air samples immediately above the cover material and subjecting them to standard gas analysis procedures or a gas spectrometer. The next step is to sink test probes at strategic locations in the fill to collect LFG samples, undiluted by air, for methane and carbon dioxide analysis as well as for other constituents. If reasonably accurate annual records of solid waste emplacement within general areas of the landfill are not available with at least approximate composition or source, it may be necessary to obtain waste samples at various locations by taking shallow and deep borings. The purpose of the gas and waste sampling and analysis is to make certain that the landfill can be expected to generate gas at a high enough rate over an extended period of time to make gas recovery practical and economically viable.

One or more test wells should be sunk and operated at different vacuum levels to determine LFG flow rates with gas samples analyzed to determine the optimal suction pressure the fill can support without ingesting air into the waste. Based on the maximum negative pressure that can be supported by the cover material and the waste permeability, the radius of well influence can be calculated and plans for the wells and collection system prepared. Wells should be no deeper than about 80 percent of the fill depth and constructed as depicted in Figures 21 and 22. More details on well design and spacing are included in the reports on the Palos Verdes, Mountain View and Shelton-Arleta projects.[1,2,3,25]

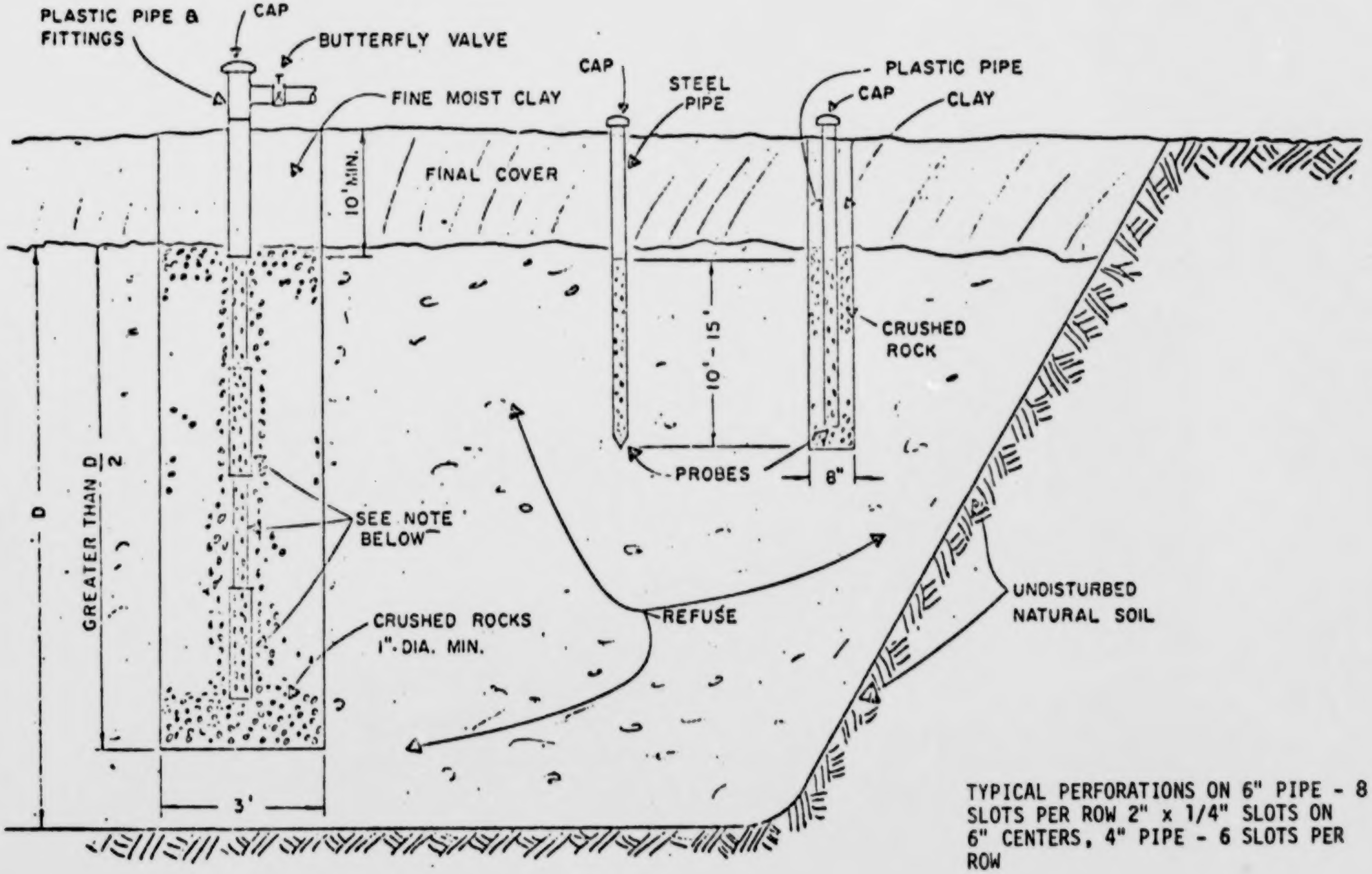
LANDFILL OPERATIONS

There are a number of operational techniques that can be considered for potential enhancement of LFG generation that do not constitute design features per se, although the addition of water for maintaining desirable moisture content of the waste requires proper collection and removal of leachate whether recycled or not. Such techniques include the initial application of water to bring as received waste to the desired moisture level during spreading and compaction; shredding to increase surface area, achieve greater compaction, and possibly eliminate the need for daily cover; seeding with sewage sludge to accelerate growth of bacterial colonies; measuring pH of recovered leachate and adding substances to achieve desired pH before recycling; and using a highly permeable daily cell cover that will not significantly impede upward LFG migration.

Each operating technique is briefly discussed and evaluated according to available information, together with cost estimates and potential cost-effectiveness of those for which information is available.

Single Water Application

Another possibility for providing the moisture necessary to enhance gas generation is to add the required amount of water at the time the refuse is placed in the landfill. Moisture content of solid waste as received generally ranges from 15 to 25 percent. Water will have to be added to bring this to a level between 50 and 60 percent. The use of a water truck or, if feasible, a less expensive system consisting of hoses with spray nozzles and one or two laborers generally is all that is needed to wet down the waste after spreading. An increased operational cost of $100 to $150 per day ($30,000 to $47,000 per year) would result based on six day operations.


PLASTIC PIPE & FITTINGS
CAP
BUTTERFLY VALVE
FINE MOIST CLAY
10' MIN.
FINAL COVER
CAP
STEEL PIPE
PLASTIC PIPE
CAP
CLAY
CRUSHED ROCK
10' - 15'
PROBES
8"
SEE NOTE BELOW
CRUSHED ROCKS 1" DIA. MIN.
REFUSE
UNDISTURBED NATURAL SOIL
D
GREATER THAN $\frac{D}{2}$
3'

TYPICAL PERFORATIONS ON 6" PIPE - 8 SLOTS PER ROW 2" x 1/4" SLOTS ON 6" CENTERS, 4" PIPE - 6 SLOTS PER ROW

Figure 21. Typical landfill gas recovery well and probes.

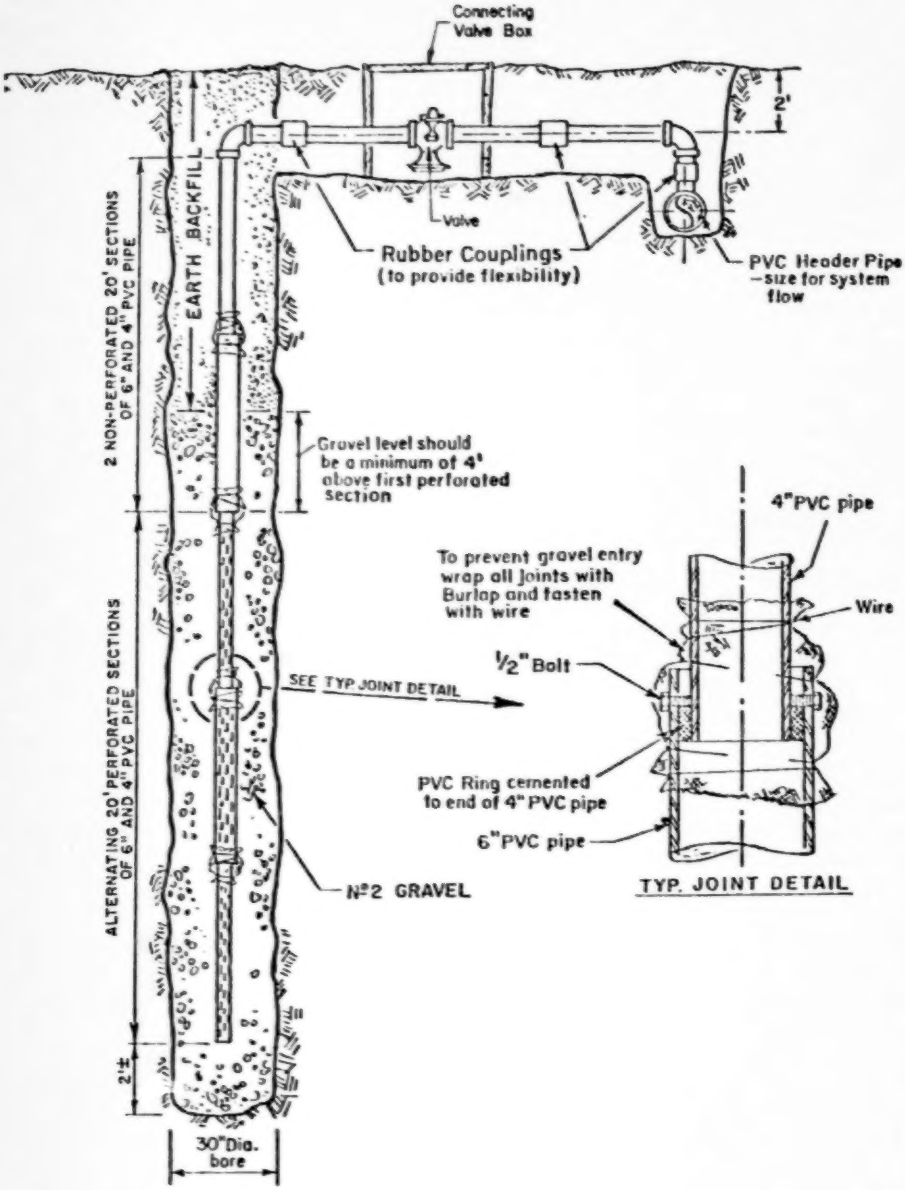

Connecting Valve Box
2'
EARTH BACKFILL
Valve
Rubber Couplings (to provide flexibility)
PVC Header Pipe -size for system flow
2 NON-PERFORATED 20' SECTIONS OF 6" AND 4" PVC PIPE
Gravel level should be a minimum of 4' above first perforated section
4"PVC pipe
To prevent gravel entry wrap all joints with Burlap and fasten with wire
Wire
½" Bolt
SEE TYP. JOINT DETAIL
ALTERNATING 20' PERFORATED SECTIONS OF 6" AND 4" PVC PIPE
PVC Ring cemented to end of 4" PVC pipe
6"PVC pipe
Nº2 GRAVEL
TYP. JOINT DETAIL
2'±
30"Dia. bore

Figure 22. Palos Verdes Landfill gas collection well and telescoping pipe configuration design.

Refuse Shredding

Because shredded waste has a greater surface area to volume ratio than raw waste it may be more susceptible to biological processes and conceivably could generate LFG at a greater rate than raw waste. Moreover, it is reported that shredded waste does not require daily cover.[55] Costs of shredding refuse vary from about $5.50 to as much as $16.50/t ($5.00 to $15.00/T). If shredding is performed as part of the landfilling operation, its cost must be recovered from increased LFG production. If done as part of a resource recovery process, then the shredded waste is a by-product and does not increase the cost of the landfilling operation.

In landfill operations in which only a portion of the incoming waste is shredded, the LFG generation rate might be enhanced by placing the shredded material in thin layers distributed throughout the unprocessed refuse. The shredded waste is believed to act as a seed material layer for accelerated microbial growth. Use of shredded waste is reported to obviate the need for daily cover which would enhance LFG collection and possibly permit greater spacing between adjacent recovery wells. However, no data is available that permits an evaluation of the effectiveness of this technique compared to its costs.

Use of High Permeability Cover

The placement of daily cover results in the landfill developing as a series of separate waste cells. This cover, if of low permeability soil, can prevent or retard the movement of moisture, methane forming bacteria and nutrients, resulting in reduced LFG generation. The daily cover can also retard movement of LFG within the influence area of the well, requiring greater negative pressure and causing air ingestion at the surface. However, the many benefits of daily cover make it generally undesirable to eliminate it from a landfill operation. Daily cover is necessary to reduce odors, disease vectors, rodents, litter, aesthetic impact and many of the other potentially negative aspects of a landfill.

Alternative approaches are the use of high permeability cover material; or the removal on the interior daily cover just prior to each successive lift being placed. The landfill then ultimately would consist of a single large cell rather than a series of many small cells.

It has been observed during the drilling of wells in some deep landfills that had been constructed using a permeable cell cover that no evidence of cell structure or cover material layers were evident. This was attributed to the sifting of the cover soil through the refuse as a result of vehicular traffic vibration and water transport. The cost would be small unless the permeable cover material had to be imported. There is no information available on the effects of these techniques, so cost-effectiveness cannot be estimated.

Sewage Sludge Seeding

Spreading raw or digested sewage sludge atop each landfill cell before spreading the daily cover conceivably could hasten the generation of LFG. However, it is also possible that exposure of sludge to the air during spreading could impair activity or even kill the bacteria colonies such that no advantage whatever is obtained. Until more specific research and test results on this technique become available, its potential value cannot be judged.

Leachate Recycling with pH Control

This technique was discussed in the subsection on design under leachate recycling. When leachate collection and recycling is included in the landfill development, it requires little more equipment or expense to periodically sample the leachate and modify its pH. Until more specific data is obtained on the precision with which pH control should be applied and the ramifications of different pH values on the rate of LFG generation, the applicability of this technique cannot be evaluated.

SUMMARY

Table 29 lists in summary form alternative design and operations techniques that could enhance LFG generation. Obviously, the design techniques apply only to new landfills or the sections of established ones that have yet to be filled.

Among the alternative approaches to site lining (bottom and sides), use of impervious soil, if available, is by far the lowest cost material that would be needed to prevent leachate percolation into the ground water table whether LFG recovery is included in the landfill development or not. If suitable low permeability soil must be imported, the distance will determine the degree of competitiveness with other alternatives such as clay treated on-site soil. Use of a reliable film barrier requires careful placement that can be several times more costly than impervious soil, as is also the case with sealant covered asphalt cement which can be used only over a highly stable base.

Among moisture control techniques, leachate collection and recycling appears competitive with water distribution below the top cover and is to be preferred if permitted by local water quality control regulations. Usually, where it can be demonstrated that the possibility of leachate seeping through the bottom lining is virtually negligible, this approach is likely to be permitted.

Concerning the operations alternatives, there is insufficient information available with which to make evaluations or even postulate probable effectiveness. If water loss with LFG is substantial, then a one time addition of water to the waste prior to daily cover is likely to be insufficient over the long term. The subject of waste shredding prior to landfilling has been in contention for some time and at best its benefits are not likely to offset its high cost. Use of a permeable daily cover that will temporarily prevent vector attraction but permit moisture and gas passage can be effective in reducing landfill gas internal flow resistance, but will not be

TABLE 29. DESIGN AND OPERATIONS ALTERNATIVES FOR LANDFILL GAS GENERATION ENHANCEMENT

Alternative	Potential effectiveness	Cost range ($/sq m)[a]
Site Lining		
Impervious soils	Effective if permeability low	0.25 to 0.42
Treated soils	Effective if permeability low	1.50 to 1.92
Film barrier	Effective with proper base preparation and cover protection	1.05 to 4.60
Asphalt cement with sealant	Effective if properly installed on firm base	3.00 to 4.05
Moisture Control		
Water distribution below cover	Highly effective	0.21 to 0.42
Semi-permeable soil with humectant	Effective if kept moist	0.03 to 0.04 (add 1.00/yr/sq m operating cost)
Controlled uniform negative pressure below cover	Effective if carefully balanced by wells with half normal spacing	0.63 to 0.84 (additional cost for recovery subsystem)
Leachate Collection and Recycling	Effective; pH control may be required	0.13 to 0.29 plus cost of neutralizing chemicals
Operations		
Single water application (truck or hose/spray nozzle)	Effective initially; long term affects unknown	0.02 to 0.03
Waste shredding without daily cover (final cover only)	Affects unknown; may hasten initial LFG generation and should increase waste permeability	4.18 to 8.63 per ton received
Permeable daily cover	Increase ease of movement of LFG within confines of landfill	No additional cost if suitable soil available
Sewage sludge seeding of waste	Affects unknown; may shorten LFG generation initiation time	0.25 to 0.42 (drop charge may exceed spreading costs)
Leachate recycling with pH control	Effective	0.13 to 0.29 plus cost of neutralizing chemicals

[a] Costs estimated for 40 ha (100 ac) fill area landfill.

very effective in preventing odors from eminating from the cell.

The effect of seeding solid waste with sewage sludge is not known at present and until controlled tests can be constructed, this technique cannot be evaluated. Leachate recycling with pH control is listed under both operating techniques and design approaches because it requires special facilities to be designed and constructed in the landfill from its inception.

Overall, the results of this evaluation emphasize the need for more definitive data and information on moisture effects and interactions on gas recovery. All that can be stated at this time is that, as indicated in Table 29, several of the design and operations techniques are estimated to be reasonable in terms of cost provided an appreciable increase in LFG recovery rate, on the order of at least 10 percent, results. To make this determination, carefully designed and controlled full scale experiments appear to be required. This subject is more fully discussed in the next section.

SECTION 7

PROJECT SUMMARY - RESULTS, CONCLUSIONS AND RECOMMENDATIONS

This section brings together and discusses in more detail the findings and conclusions of this study on the state-of-knowledge of landfill gas generation, processing and utilization. It concludes with recommendations for research for demonstration projects needed to develop the necessary additional data or refine existing information in order that the technical and economic feasibility of LFG to energy conversion systems can be clearly established.

RESULTS AND CONCLUSIONS

The results and conclusions deal primarily with the adequacy of basic data on gas generation, approaches and techniques for optimization of gas generation and recovery, and the costs and economics of LFG system alternatives compared with other waste-to-energy process systems.

Basic Data Adequacy

Evaluation of the data available on landfill gas generation phenomena reveals a dearth of hard empirical data on such basics as theoretical and practical gas generation rates and total quantity of gas that can be expected per unit quantity of typical solid waste, or on an organics content basis. The very nature of anaerobic decomposition of organic materials in landfills over long periods of time after waste emplacement makes this difficult. It is fairly well established that methane (together with carbon dioxide) generation rate increases rapidly during the first 3 to 12 months, diminishes gradually from the maximum rate over a period of 5 to 10 years, and then diminishes more rapidly during the declining period that may last an additional 10 to 30 or more years.

Gas generation depends upon numerous variables such as waste composition, moisture content, cell structure, landfill depth and internal temperature. Consequently, simulation or replication of landfill processes are difficult and expensive to reproduce in the laboratory under conditions in which variables can be controlled, or, at least measured. Although chemical-physical analytical models of the multi-stage decomposition process have been developed, knowledge of the maximum quantity of gas generated per unit of refuse is based on only theoretical calculations. This is because almost all organic waste materials are comprised of some relatively inert or biologically refractory material which resists decomposition and is not completely digested or, if so, only very slowly.

While analogies have been made to model controlled environment, biodigestion of solid waste and 5 to 10 percent sewage sludge in a water slurry (a process that proceeds virtually to completion within about 30 days), only maximum gas production rates and total unit quantities have been deduced. Because the landfill environment is markedly different from the waste-sludge-water slurry digester tank, the maximums cited are unlikely to be realized in a landfill environment.

Composition of landfill gas, however, is well established because this is a relatively easy measurement once wells have been sunk and stable gas generation conditions have been established. Even so, reliable LFG composition data ranges from about 45 to 60 percent methane; the remainder being carbon dioxide with small amounts of nitrogen, oxygen, hydrogen sulfide, other trace gases, and water vapor at the gas saturation level. The factors that influence methane content of landfill gas are not precisely known at this time due to imprecise data on quantity and variation of waste composition amoung the numerous cells of the landfill or even within the area of influence of a single gas recovery well.

This lack of a reasonable level of certainty or confidence in the basic data upon which the economics of landfill gas recovery and processing systems are based is one major factor deterring progress in implementation of such systems.

Gas Generation and Recovery Optimization

Several alternative design approaches and operating techniques for optimizing gas generation and recovery have been discussed (Section 6), although only in qualitative rather than quantitative terms because of the lack of data on which to base quantitative estimates. While gas migration control is compatible with optimization of gas recovery, there are numerous unknowns or uncertainties regarding use of non-permeable bottom and side barriers to gas flow in terms of effects of higher gas partial pressures and possible greater concentrations of metabolic wastes or gases (e.g., hydrogen) on methanogenic organisms. An optimal surface cover material for landfills with gas recovery is one that permits infiltration of water and prevents passage of gas. However, experimental or empirical data that would permit selection of the most cost-effective methods are not available.

Optimum moisture content of the emplaced waste to maximize gas generation, related loss of moisture (water vapor in the recovered gas and evapotranspiration), moisture produced by the bacterial organisms, together with the amount of water that may have to be added to maintain maximum gas generation cannot be addressed in specific quantitative terms. However, methods for controlling moisture content of the waste prior to emplacement in the landfill and methods for adding water thereafter have been evaluated.

Leachate control and possible recycling have some merit. When leachate is prevented from percolating into underlying ground water either by locating landfills at sites with underlying impermeable geological structures or by placement of artificial barriers, downward migration of landfill gas, in all likelihood is simultaneously prevented. This is particularly true if the bottom material, when wet, becomes impervious to gas passage, or an artificial barrier material is used that is impervious to gas passage. The use of recovered leachate to maintain moisture levels in emplaced solid waste is another approach discussed and evaluated for applicability and cost. However, the influences of both pH control and leachate recycling on methane-forming organisms is not adequately known although the preferable range of pH that is believed to enhance methane formation is known (see Section 4).

The entire subject of pre-processing or preparation of solid waste prior to landfilling to maximize gas generation, in terms of rate, total quantity per unit quantity of waste, and methane content, is open to supposition. There may be some improvement in gas generation rate resulting from shredding waste prior to emplacement due to potentially greater surface exposure to methanogenic organisms. Because of the relatively high cost of shredding, however, the resulting increase in revenues may not be sufficient to pay for the pre-processing. However, the revenues from the recovery and sale of metals and glass (which normally requires shredding) might totally or substantially cover shredding costs such that pre-processing becomes economically viable. Whether removal of metals from the waste will enhance methane generation (by eliminating most of the metallic oxides which may deter methanogenic processes directly of indirectly by decreasing pH values) also is not known. There are obviously numerous factors involved in the analysis and selection of techniques for enhancing methanogenic processes that remain uncertain.

The cost and economic analyses presented in Section 5 show that recovery and use of landfill gas in its raw state, or processes to remove water vapor or both water vapor and carbon dioxide, can be economically viable even with gas generation rates, total quantities and composition toward the low ends of the quantitative ranges. Thus, improving the level of knowledge and reducing uncertainties in these areas is likely to contribute most to avoiding those complex and expensive processing and utilization alternatives which, based on existing data, promise a lower and more marginal return on investment. Emphasizing the need for better information in these areas is the apparent fact that market potential for upgraded landfill gas near or equal to the heating value of natural gas, or steam or electricity generated using unprocessed landfill gas, generally is considerably better than for raw gas.

Cost and Economics

The cost and economic analysis contained in Section 5, in general, is based on mid-to-low range estimates of landfill gas quality and a conservative ten-year period of gas generation at rates that warrant recovery and processing. For the simplest processes and those that employ direct utilization of recovered gas (which also have the lowest costs and most favorable economics), it can be argued that more reliable and higher confidence level data are not needed. However, because processing and utilization equipment characteristically have intrinsic operating lives of 20 or more years, the problem of justifying purchase and installation of equipment with a 20-plus year useful life for a landfill gas recovery project that promises only a 10-year economic gas generation-recovery period will undoubtedly arise.

Consequently, a major uncertainty in the cost and economic analyses centers on the period of useful gas generation. Useful is defined as generating gas at a rate sufficient to warrant recovery by originally emplaced wells, collection pipelines and pumping blowers or compressors without substantial reduction in facility capacity. Overpumping the wells would increase impurities in the gas (primarily nitrogen) or deter or cause gas generation to cease due to oxygen poisoning of the methanogenic organisms.

Another major uncertainty concerns gas recovery rate and composition stability over time. The basic marketability of landfill gas in any form depends upon ability to meet customer quality specifications and demand over a relatively long term. No potential purchaser is likely to invest in the necessary facilities to use substandard fuel gas unless there is assurance of a reasonable number of years over which to amortize this investment. Moreover, unless an adequate number of years of landfill gas use can be assured, the increased amortization rate may make use of this gas uneconomical or noncompetitive with other fossil fuels or waste-to-energy processes.

Obtaining more reliable basic data on the generation of landfill gas and on optimization of rate and period of useful generation is virtually mandatory in order for the potential of this fuel to be realized on a widespread commercial basis. Additional research and development, and demonstration projects are needed to substantiate, if not improve upon, the values selected and used in this study.

RESEARCH AND DEVELOPMENT, AND DEMONSTRATION PROJECT RECOMMENDATIONS

This subsection identifies and briefly discusses research, development and demonstration projects on landfill gas generation, processing and utilization believed necessary to eliminate uncertainties from the existing body of information on the subject.

R&D demonstration needs were developed from assessment of the material presented in Sections 4, 5, and 6 which essentially describe the existing level of knowledge and state-of-the-art in recovery, processing and utilization of landfill gas as a supplementary fuel. The material contained in those three sections resulted largely from the review, study and analysis of available literature, from unpublished information available to the study participants either from their own projects or from those pursued by others, and from additional analysis performed especially for this study. Only limited new basic information about landfill gas recovery, processing and utilization has been developed during this study because its emphasis was to pull together, analyze and refine existing information, perform additional analysis and present it in a concise, cogent and usable fashion within the bounds of a single report. The review work performed, however, does suggest some new approaches and improvements to existing tehcniques for optimizing landfill gas recovery, processing and utilization.

The major tenets underlying the R&D and demonstration projects suggestions are existing and prospective markets for use of landfill gas as a supplementary fuel in relatively widespread commercial and industrial applications. The diminishing supply of natural gas, increasing importation of crude oil with its adverse international balance of payment ramifications, and the similarity of landfill gas to natural gas in terms of its clean-burning qualities all serve to increase interest in the potential for widespread utilization. Based on recent experience with solid waste resource recovery (materials and energy), the suggested projects are needed to unequivocably demonstrate the technological feasibility and provide the economic viability data required by both public and private entities before widespread implementation of landfill gas recovery/processing/utilization is likely to occur.

RESEARCH AND DEVELOPMENT NEEDS

The suggestions for research and development to improve basic landfill gas generation and recovery data, and to optimize gas generation and recovery performance are representative of the work required in the near future. No attempt has been made to design projects in detail or optimize their potential payoff in meeting improved basic and new data requirements. Although research and development reports and lists of ongoing EPA and DOE projects have been taken into account, there may be work in progress that will produce some or all of the needed data. If so, these suggestions will confirm the value of such projects and perhaps validate further funding that may be required for their completion.

Table 30 lists suggested landfill gas research and development projects by title, objectives, and gross estimates of project duration and direct professional labor by work category. Each project is briefly discussed below in terms of need, objectives and techniques involved.

1. Improved baseline Data Development for Landfill Gas Generation and Recovery

Basic data on landfill gas generation in terms of gas generation rate, gas composition (initially and over time) and total quantity of gas (particularly the methane content) produced per unit of total waste or organic components are imprecisely known. These gas characteristics are basic to unraveling the costs and economics of gas recovery/processing/utilization and dispelling existing uncertainties which presently tend to retard implementation of gas recovery systems.

Objectives

To develop, by means of a combination of analytical models, laboratory simulation, and full scale controlled tests, improved

TABLE 30. SUGGESTED LANDFILL GAS RESEARCH AND DEVELOPMENT PROJECTS

Project title	Project objectives	Estimated duration (months)	Estimated work content (person-months)		
			Analysis/design/reports	Laboratory work	Field work
1. Landfill Gas Generation/Recovery Improved Baseline Data Development	Develop reliable and improved basic data on gas generation characteristics	8 to 12	6 to 12	3 to 6	3 to 6
2. Landfill Gas Generation Optimization Techniques Test and Evaluation	Design experiments, test and evaluate alternative optimization techniques	12 to 18	6 to 12	6 to 12	6 to 12
3. Landfill Design Optimization for Gas Recovery (Existing and New Landfills)	Determine most cost-effective design parameters for gas collection at existing and new landfills including geometry, depth, pollution control.	8 to 12	6 to 12	1 to 2	6 to 12
4. Gas Recovery Well and Collection System Design Optimization	Determine best well configuration, influence area, spacing, pumping and collection system	6 to 9	8 to 12	1 to 2	6 to 12
5. Leachate Recycling and other Liquids Use to Enhance Landfill Gas Generation	Test and evaluate leachate and other liquid waste introduction to increase gas generation rate, quality, etc.	8 to 15	4 to 8	4 to 6	6 to 12
6. Improvements in Energy Recovery Efficiency of Landfill Gas Generation Recovery	Develop, test and evaluate methods to improve basic energy recovery efficiency (gas energy content vs waste energy content)	8 to 12	6 to 12	6 to 12	-
7. Benefits of Prelandfill Processing for Improving Landfill Gas Generation	Test and evaluate benefits and costs of various prelandfilling waste processing including inorganics recovery	8 to 12	8 to 12	4 to 8	6 to 12

(continued)

Table 30. continued

Project title	Project objectives	Estimated duration (months)	Estimated work content (person-months) Analysis/design/reports	Laboratory work	Field work
8. Refined Cost and Economic Analysis of Landfill Gas Recovery/Processing/ Utilization	Develop refined costs and economics of alternative landfill gas recovery, upgrade processes and utilizations based on improved baseline and optimization data	4 to 6	10 to 12	-	-
9. Handbook for Landfill Gas Recovery/Processing/Utilization	Handbook covering basic design, common variables and operational information	6 to 9	6 to 12	-	-
10. Evaluation of institutional Constraints to Landfill Gas Utilization	Analysis of deterrants to use of landfill gas, incentives and other aspects to encourage use	6 to 9	6 to 8	-	-
11. Evaluation of Equipment Changes for Utilization of Landfill Gas	Determination of boiler, furnace, gas turbine, gas engine changes necessary to use raw and processed landfill gas including costs and economics	6 to 9	8 to 10	-	-

data on gas production rates, composition and variations over time, and most important, the total amount of methane that can be produced per unit of wastes or organics quantity over the total or half-life of the process.

Techniques

Analytical models treating all relevant anaerobic decomposition gas generation variables will be developed. Numerous samples obtained from landfills of different ages where original waste composition is reasonably known should permit laboratory determination of degree of decomposition as a function of time and moisture content in order to provide data for the models. Laboratory simulation of the landfill decomposition process or full scale controlled tests should provide additional data. Laboratory sample water-slurry analogues may permit additional correlation with landfill sample data. Accurate estimates of degree of decomposition and gas characteristics over time can be established by a combination of these analytical, sampling and laboratory simulation techniques. A preliminary evaluation of techniques and their relationships is advisable to assure a sound project.

2. Landfill Gas Generation Optimization Techniques Tests and Evaluation

A number of techniques have been suggested that might prove useful in improving landfill gas generation, such as increase and maintain a high moisture content, shred waste before landfilling, seed solid waste with sewage sludge and recycle leachate, using chemical additives to control pH. This may improve digestibility of certain organic waste components, shorten time to initiation of anaerobic decomposition or significantly enhance gas generation rate or quality of methane production.

Objectives

Conduct experiments using both laboratory simulation and full scale landfill environments to test and evaluate, singly and in appropriate combinations, techniques to enhance landfill gas generation which could lead to optimization of the use of one or a combination of these techniques. Costs and benefits can then be evaluated against resulting gas generation characteristics. Those techniques that prove beneficial will be recommended for use.

Techniques

Use of laboratory simulation should be capable of discriminating among alternative and competing optimization techniques by comparative measuring of gas generation rate, quantities and characteristics even though simulation values may not precisely replicate full scale landfill environments. Promising techniques can then be reproduced in limited full scale landfill test volumes and results compared.

3. Landfill Design Optimization for Gas Recovery

Several possibilities for optimal design of landfills for gas recovery are discussed in Section 6 of this report. There is an apparent need to perform more detailed theoretical analysis and testing of these techniques, particularly the use of impervious and permeable materials both to constrain gas and moisture, and to permit controlled passage. Geometry of landfill cells and methods to cause a landfill composed of numerous cells to perform like a single waste deposit are also of interest. Leachate control and possible recycling of leachate also are techniques that need specific experimentation.

Objectives

Further evaluate landfill design techniques analytically and test and evaluate alternative methods for improving recovery effectiveness, moisture control, well influence area effectivness, gas pumping methods, etc.

Techniques

Development of landfill geometric configurations can be accomplished analytically. Experiments can be designed for laboratory evaluation of permeable and impermeable material barriers to optimize moisture passage while minimizing gas penetration. Mechanical disruption of cell barriers as a new cell is placed on top also is of interest and requires full scale experimentation.

4. Gas Recovery Well and Collection System Optimization

Analytical and experimental work is needed to optimize gas recovery well design, area of influence diameter to depth relationships, and proper landfill cell compaction to optimize well influence areas and minimize both capital and operating gas recovery system costs. Although existing wells appear to function satisfactorily, their efficiency and effectiveness are not adequately known.

Objectives

Develop optimal landfill gas recovery well design as related to waste composition, density and geometry, and influence area, spacing and depth. Also, evaluate and select the best materials of construction, pumping equipment, pressure monitoring probes, etc.

Techniques

Much of this project can be accomplished via analytical models and simulation. Equipment performance can be measured and compared under test laboratory conditions in many instances. Promising systems can then be installed at full scale landfills and performance measured both on an absolute and relative basis.

5. Leachate Recycling and Other Liquids Use to Enhance Landfill Gas Generation

The possibility of recirculating landfill leachate for pH as well as leachate control is discussed in Section 6. Other waste liquids may have useful application for pH and moisture control to enhance gas generation. Little is known of the effects of alternatives and experimentation appears to be required using both laboratory simulation and full scale tests.

Objectives

Determine effects of leachate recycling on gas generating landfills and the potential utility of other non-toxic liquid wastes for either pH or moisture control, or both. Also, water-slurry biodigestion of solid wastes with a small percentage of sewage sludge suggests that weak acid or alkaline hydrolysis may increase the digestibility of cellulosic materials.

Techniques

Much of the work of this project can be accomplished in the laboratory under carefully controlled conditions. Samples of typical solid waste can be pretreated to determine if hydrolysis improves gas generation quantities per unit of waste. Leachate and other liquid wastes can be used on waste samples to determine effects on gas generation. If techniques prove of value, then tests can be conducted in controlled areas of full scale landfills.

6. Improvements in Energy Recovery Efficiency of Landfill Gas Generation/Recovery

Techniques that can significantly increase the amount of energy recovered as landfill gas compared with that originally contained in the waste appear to be needed. Shredding and/or hydrolysis of the waste prior to emplacement, seeding with sewage sludge during emplacement, and removal of metals and most other inert materials prior to landfilling appear to be other possibilities.

Objectives

Determine if certain types of waste pre-processing and pre-treatment prior to or immediately after emplacement can increase recovery efficiency; evaluate cost effectiveness of promising techniques.

Techniques

Initial work can be accomplished entirely in the laboratory. Waste samples can be prepared by alternative pre-processes and landfill decomposition can be simulated by bio-digestion tests which measure total gas generation and degree of decomposition. Promising techniques can be further evaluated via full scale landfill tests, with controlled emplacements of differently preprocessed or pretreated wastes. Performance can be measured by comparative analyses and waste composition as a function of age.

7. Benefits of Waste Processing for Improving Landfill Gas Generation

Improvement in the economic performance of LFG generation and recovery systems appear to exist by removing non-biodegradable materials from the waste prior to landfilling. This approach potentially improves the volumetric efficiency of landfills for more concentrated gas generation and reduces the number of wells required to collect the gas because all or nearly all of the waste emplaced will be organic. Also, revenues derived from recovery and sale of metals and glass may reduce the cost of energy recovery or cover the cost of otherwise uneconomic pre-processing.

Objectives

Study applicability of various pre-processing techniques for improving economics of LFG production and recovery. Determine economic advantages and disadvantages of pre-emplacement waste segregation and recovery of inorganics to achieve more efficient use of landfill space and more effective use of landfill gas collection systems.

Techniques

Analytical results are to be verified through laboratory tests and evaluations to the extent possible. Subsequent tests and evaluations in limited landfill areas under controlled conditions are suggested.

8. Refine Cost and Economic Data on Landfill Gas Recovery/Processing/Utilization

Improved baseline data on landfill gas production and recovery, together with information on optimization techniques for more efficient systems, will permit more accurate preliminary system design and cost estimating.

Objectives

Refine estimates of capital and operating costs for alternative recovery, processing and utilization systems at various capacity levels or flow rates using improved baseline gas generation and recovery performance data. Compare detailed economic analyses of best alternatives with fossil fuel and other waste-to-energy systems.

Techniques

Preliminary design for complete landfill gas recovery, processing and utilization alternatives at no less than three capacity levels can provide the data for estimating capital and operating costs over the useful life of the system. Curves of unit capital and operating costs plotted as functions of capacity will illustrate economies-of-scale. Economic analysis will allow prediction of financial performance of alternative systems under varying market conditions and pricing structures for recovered materials and synthetic fuels. Sensitivity analysis will cover uncertainty in fuel and materials prices for future periods.

9. Handbook for Landfill Gas Recovery/Processing/Utilization

To foster widespread consideration and implementation of LFG waste-to-energy systems, a detailed handbook on applications analysis, and selection of most appropriate alternatives suitable to specific local conditions would be most helpful. Also needed are suggestions on market research and analysis, best uses for the fuel, steam vs. electricity conversion, alternative methods for financing capital costs, and split ownership arrangements with utilities or large industrial/commercial energy users. This handbook would parallel various other handbooks that have already been prepared for solid waste resource recovery, incineration, etc.

Objectives

Provide data, information, analysis techniques and suggestions for conduct of feasibility studies, selection of system alternatives, marketing and contracting for sale of products, system design and construction, and operation of landfill gas recovery, processing and utilization systems. Also to be provided are basic safety and security techniques, storage methods for interruptable customer deliveries, etc.

Techniques

Essentially, the handbook will be a compilation and analysis of data and information presently available in the literature with added explanation of techniques suggested and how to evaluate results. Dependent upon timing of handbook preparation, a series of handbooks such as were prepared for resource recovery, could possibly be developed incrementally as additional data and information becomes available.

10. Evaluation of Institutional Barriers to Landfill Gas Utilization

Initial attempts to market dehydrated LFG and LFG upgraded to near natural gas standards have been confronted with considerable reluctance on the part of potential users to contract for purchase of this gas. Why potential industrial users are reluctant is not precisely known, but the only current purchasers are two utilities (Pacific Gas & Electric Company, Mountain View Projects; and Southern California Gas Company, Palos Verdes Project) who are participating in demonstration programs. Also, the Los Angeles Department of Water & Power has contracted to purchase the landfill gas from the Sheldon-Arleta Landfill. In the private sector, one chemical company has signed a contract for purchase of dehydrated gas from the Azusa-Western Landfill project. It is reported that no firm sales of recovered LFG have yet been accomplished in other areas of the nation.

Objectives

Determine why potential users are reluctant to purchase LFG and what is necessary in the form of incentives, technical assistance, reliability and quality guarantees, etc., to encourage purchase and use. Recommend appropriate pricing policies, etc.

Techniques

Approaches which can be used include mail questionnaires directed to large commercial, industrial and institutional fuel users, particularly those threatened with future reduction or cutoff of their natural gas supply. Selected responses would be followed up with interviews of plant engineers and corporate executives to discuss what would encourage use.

11. Evaluation of Equipment Changes for Utilization of Landfill Gas

Use of any form of LFG usually requires certain modifications to boilers, furnaces, gas turbines and reciprocating gas engines, storage and compression systems, and possibly even distribution trunklines of gas utilities.

Objectives

Determine required alterations to combustion equipment for use of dehydrated and upgraded forms of LFG in typical steam generating equipment. Prepare cost estimates for alterations to existing equipment or required new equipment, and determine overall economics of LFG use. Prepare advisory memoranda for suppliers and potential users of landfill gas to help marketing efforts.

Techniques

Analyze combustion characteristics of different grades of LFG to determine fuel-air ratios, flame temperatures, flame propagation, corrosion problems, storage and pressure requirements, and burner characteristics. Determine necessary alterations and substitutions, time required for modifications, and tests or "shake down" evaluations that may be required and aggregated costs of such changes to representative installations.

DEMONSTRATION PROJECT NEEDS

Current Activity

There are a number of major LFG recovery, processing and utilization projects in various stages of development or operation in the United States at the present time. Table 31 lists major projects on which some information is available, although only one or possibly two were in regular commercial operation at the end of 1977. Two additional projects are scheduled to begin commercial operation in 1978 and the others are in various stages of evaluation, planning or design. Only the Mountain View Landfill gas recovery project has received EPA monitary support, the costs being shared with the Pacific Gas & Electric Company.

Of the three projects that have progressed either to the stage of commercial operation or initial shake down operations prior to beginning regular operations, two (Mountain View and Palos Verdes) employ triethylene glycol water vapor removal and molecular sieve carbon dioxide removal to upgrade the gas to near natural gas specifications. The third project at the Azusa-Western Landfill only removes water vapor with triethylene glycol before delivery to a nearby chemical plant. The only other project that appears reasonably certain to be completed is the Sheldon-Arleta Landfill facility sponsored (and owned) by the Departments of the City of Los Angeles, California.

Any one of these ongoing or soon to be in operation projects could provide needed performance and operations data to establish the technical feasibility of LFG recovery and processing to produce a dehydrated gas with about one-half the heating value of natural gas or upgrade processing to deliver a gas approximating the characteristics and heating value of natural gas. Certainly, cost and economic data will be available from the Mountain View project partially funded by EPA, but whether or not similar data will be made available on the Palos Verdes and Azusa-Western projects is uncertain. Private industry typically is relucant to reveal details on performance and economics lest they compromise their competitive position or industrial secrets.

Demonstration Project Recommendations

Considerable factual data on the technological feasibility and economic viability of landfill gas recovery, processing and utilization is required before this waste-to-energy method can be expected to achieve widespread application. In fact, several of the projects listed in Table 31 are understood to have been suspended awaiting "hard" favorable data from initial projects.

TABLE 31. MAJOR LANDFILL GAS RECOVERY/PROCESSING/UTILIZATION PROJECTS IN THE UNITED STATES

Project Name	Location	Recovery System and Gas Rate	Processing System	Status and Utilization	Sponsors/Owners
Mountain View Landfill	Mountain View, Calif.	20 wells, average fill depth 40 ft, 1 million scf/D 700 cfm	Compression of 400 psig Triethylene Glycol water removal and Molecular Sieve carbon dioxide removal to produce 750 BTU/scf gas	Scheduled to begin operation by end of 1977 Gas to be introduced into PG&E natural gas transmission line resulting in 975 BTU/scf mixed gas	City of Mountain View, Pacific Gas & Electric Co. with EPA grant for partial funding
Palos Verdes Landfill (CA Class I)	Rolling Hills Estates, Calif. (Los Angeles Basin-coastal)	8 wells, average fill depth 120 ft, 2 million scf/D 2500 cfm	Triethylene Glycol water removal and Molecular Sieve carbon dioxide removal to produce 1000 BTU/scf gas	In operation since summer of 1975 Gas purchased by So. Calif. Gas Co. introduced into local transmission system	Reserve Synthetic Fuels Inc., Los Angeles County Sanitation Districts (LACSD), So. Calif. Gas Co.
Azusa-Western Landfill	Azusa, Calif.	11 wells, average fill depth 80 ft, 3.5 million scf/D 2400 cfm (designed for max. 3500 cfm)	Triethylene Glycol water removal providing 450 BTU/scf ± 10 percent gas	90 day shakedown completed August 1977, Commercial operations to begin Jan., 1978 Gas purchased by nearby chemical plant; potential for added industrial users	Azusa Land Reclamation Co. Southwestern Portland Cement parent Co. financed
Sheldon-Arleta Landfill	Sun Valley, Calif.	14 wells, average fill depth 130 ft, 3 million scf/D 2000 cfm	Water vapor removal to provide 450 BTU/scf gas	Recovery tests completed, collection and 1.5 mile pipeline under construction Gas to be used by LA DWP Valley Steam Plant as supplementary fuel	L. A. Dept. Water & Power, L. A. Bureau of Sanitation
North Valley (Sunshine) Landfill	Los Angeles, Calif.	Not available, average fill depth 175 ft, Not available	Triethylene Glycol water removal and Molecular Sieve carbon dioxide removal to product 1000 BTU/scf gas	Gas production survey completed; design reported to be in progress; construction pending	Reserve Synthetic Fuels, Inc.

(continued)

TABLE 31. continued

Project Name	Location	Recovery System and Gas Rate	Processing System	Status and Utilization	Sponsors/Owners
62nd Street Landfill	Denver, Col.	15 wells, average fill depth 25 ft, 3 million scf/D 2000 cfm	Not available	Design status uncertain project apparently pending Gas to be sold to adjacent asphalt plant	Property Improvement Co.
Scholl Canyon Landfill	Glendale, Calif.	8 wells, average fill depth 100 ft, 1.7 million scf/D 1200 cfm	Not available	Analysis and survey completed; Design status not available; generate 3000 kW peaking power 8 hours per day using gas	City of Glendale, Calif.
BKK Landfill	West Covina, Calif.	Not available average fill depth 200 ft, 4000 cfm estimated	Ammonia synthesis planned	Gas production survey completed; feasibility study completed; project pending	BKK Landfills Inc, BKK Corp.
Ascon Landfill	Wilmington, Calif.	Not available average fill depth 65 ft, 800 cfm estimated	Probably water removal	Planning in progress; gas survey completed; project pending; Gas to be sold to nearby industry	Watson Industrial Properties
City of Industry Landfill	Industry, Calif.	Not available average fill depth 50 ft, 400 cfm estimated	Not available	Planning and gas survey underway; Gas to be used by nearby golf club for club house space heating and hot water	City of Industry
Pasqualletti Landfill	Phoenix, Ariz.	Not available average fill depth 35 ft, 1000 cfm estimated	No processing planned	Gas survey completed and planning reported to be in progress, implementation depends on sales contract to Phoenix Tallow Works	Reserve Synthetic Fuels
Puente Hills Landfill	Whittier, Calif.	Not available average fill depth 100 ft, 1500-3000 cfm estimated	Probably none but presently uncertain	In planning stage	LACSD

(continued)

TABLE 31. continued

Project Name	Location	Recovery System and Gas Rate	Processing System	Status and Utilization	Sponsors/Owners
CID Landfill	Calumet, Ill.	Average depth 120 ft.	Not available	Gas survey completed; project pending	Reserve Synthetic Fuels
Lauer No. 1 Landfill	Menonenee Falls, Wis.	Average depth 40 ft.	Not available	Gas survey completed; project pending	Reserve Synthetic Fuels
Mountain Gate Landfill	Los Angeles, Calif.	Average depth 100 ft.	Not available	Has migration system installed; gas survey completed	City of Los Angeles, LACSD
Holtsville Landfill	Brookhaven, L.I., N.Y.	Average depth 40-100 ft.	Not available	Survey and gas migration control system contract let; recovery system will follow if feasible	Brookhaven, L.I. N.Y, Reserve Landfill Dev. Co

m = 0.3048 x ft

std cu m/min = 19.652 x MM scf/day

cu m/min = 0.02832 x cfm

kJ/cu m = 37.32 x BTU/scf

Accordingly, Table 32 lists three types of demonstration projects suggested for consideration.

1. Landfill Gas Recovery and Processing (Raw and Upgraded Gas)

   The collection, analysis and reduction of performance, operation and cost/economic data from ongoing gas recovery and processing projects is suggested. At least one facility that is delivering dehydrated gas and another that is upgrading the gas to near natural gas standards, should be included. Collection and analysis of data from multiple installations of different capacities would be highly desired.

2. Landfill Gas Recovery and Utilization (Steam and Electricity

   A similar assessment of a steam generation/steam turbine-electrical generator operation or separate evaluations of steam generation and some form of electricity generation is recommended. The cost of these demonstration projects need not exceed from one to perhaps three million dollars capital investment.

3. Environmental Effects of Landfill Gas Recovery, Processing, and Utilization

   The third demonstration project suggested is to evaluate the environmental impacts, pollution control techniques and potential mitigation measures applicable to landfill gas recovery, processing and utilization. It appears that because of the clean burning properties of landfill gas (methane) and the harmless effects of carbon dioxide and water vapor when emptied into the atmosphere, such projects will have negligible adverse impacts. Nonetheless, primary and secondary effects must be determined and evaluated. The approach suggested is to monitor the available demonstration and R&D projects.

TABLE 32. SUGGESTED LANDFILL GAS DEMONSTRATION PROJECTS

Project title	Project objectives	Estimated duration (months)	Estimated work content (person-months)		
			Analysis/design/reports	Laboratory work	Field work
Demonstration of Landfill Gas Recovery and Processing Systems (Raw and Upgraded Gas Utilizations)	Full-scale proof-of-process - gas recovery and processing technical and economic feasibility	18 to 24	6 to 12 (Data review, analysis and reduction only)	2 to 4	4 to 8
Demonstration of Landfill Gas Recovery and Utilization Systems (Steam and Electricity)	Full-scale proof-of-process - gas recovery/processing and utilizations, technical and economic feasibility	18 to 24	36 to 48	2 to 4	12 to 24
Evaluation of Environmental Effects of Landfill Gas Recovery/Processing/Utilization	Independently evaluate pollutants, pollution control and environmental impacts of demonstration projects	12 to 18	12 to 18	4 to 6	12 to 18

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